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THESIS

SYSTEMS ARCHITECTURE FOR A TACTICAL NAVAL COMMAND AND CONTROL SYSTEM

by

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March 2009

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13. ABSTRACT (maximum 200 words)

Command and control (C2) is an enigma that has been studied by military leaders and warfare analysts for hundreds of years. As a result of the numerous definitions and concepts of C2, the design of C2 systems is a challenge to systems engineers. Adding to the challenge is the understanding and integration of new operational concepts, such as Network-Centric Warfare, identified by stakeholders as necessary to meet operational needs. Through the use of a system architecture methodology, this thesis created a general vision of the system; identified the boundaries of, inputs to, outputs from, and objectives for the system; described what the system was to do with the identified inputs to produce the desired outputs; described the resources that comprised the system, the procedures by which the system was used, and the controls on the system; and proposed two alternative system architectures from which an analysis of designs could be conducted. From this methodology, numerous points of integration between doctrine and material, as well as areas for future effort and study, were identified to assist in the development and integration of net-centric systems and net-centric doctrine to meet the command and control needs of future tactical naval forces.

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SYSTEMS ARCHITECTURE FOR A TACTICAL NAVAL COMMAND AND CONTROL SYSTEM

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ABSTRACT

Command and control (C2) is an enigma that has been studied by military leaders and warfare analysts for hundreds of years. As a result of the numerous definitions and concepts of C2, the design of C2 systems is a challenge to systems engineers. Adding to the challenge is the understanding and integration of new operational concepts, such as Network-Centric Warfare, identified by stakeholders as necessary to meet operational needs. Through the use of a system architecture methodology, this thesis created a general vision of the system; identified the boundaries of, inputs to, outputs from, and objectives for the system; described what the system was to do with the identified inputs to produce the desired outputs; described the resources that comprised the system, the procedures by which the system was used, and the controls on the system; and proposed two alternative system architectures from which an analysis of designs could be conducted. From this methodology, numerous points of integration between doctrine and material, as well as areas for future effort and study, were identified to assist in the development and integration of net-centric systems and net-centric doctrine to meet the command and control needs of future tactical naval forces.

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LIST OF SYMBOLS, ACRONYMS, AND ABBREVIATIONS

AFDD	Air Force Doctrine Document
C2	Command and Control
C3	Command, Control, and Communications
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance
CEC	Cooperative Engagement Capability
CIR	Critical Information Requirement
CJCSM	Chairman of the Joint Chiefs of Staff Manual
CSG	Carrier Strike Group
CTP	Common Tactical Picture
CWC	Composite Warfare Commander
DOTMLPF	Doctrine, Organization, Training, Material, Leadership, Personnel, and Facilities
DP	Dimensional Parameter
EEFI	Essential Element of Friendly Information
EEI	Essential Element of Information
ESG	Expeditionary Strike Group
FM	Field Manual
JP	Joint Publication
LOAC	Law of Armed Conflict
MCDP	Marine Corps Doctrinal Publication
MIC	Maritime Interception Officer
MoCE	Measure of Command and Control (C2) Effectiveness
MoE	Measure of Effectiveness
MoFE	Measure of Force Effectiveness
MoM	Measure of Merit
MoP	Measure of Performance
NATO	North Atlantic Treaty Organization
NCO	Network-Centric Operations
NCW	Network-Centric Warfare
NDP	Naval Doctrine Publication
NSA	North Atlantic Treaty Organization (NATO) Standardization Agency
NSL	No-strike List
OPORD	Operational Order
OODA	Observation-Orientation-Decision-Action
OSC	On-scene Commander
OTC	Officer in Tactical Command
PPR	Pre-planned Response
R&TO	Research and Technology Organization
RFI	Request for Intelligence
ROE	Rules of Engagement

RPD	Recognition-Primed Decision Making
RTL	Restricted Target List
SAG	Surface Action Group
SATCOM	Satellite Communications
SUPP	Supplement
TST	Time-sensitive Targeting
TTP	Tactics, Techniques, and Procedures
WTP	Weapons-target pairing

GLOSSARY

Analysis: "Separation of a whole into its component parts" [Mish, 1994: 41].

Context: "A set of entities that can impact the system but cannot be impacted by the system" [Buede, 2000: 38].

Commander's Intent: "A concise expression of the purpose of the operation and the desired end state" [JP 1-02, 2008].

Doctrine: "Fundamental principles by which the military forces or elements thereof guide their actions in support of national objectives. It is authoritative but requires judgment in application" [JP 1-02, 2008].

External Systems: "A set of entities that interact with the system via the system's external interfaces" [Buede, 2000: 38].

Mission: "The task, together with the purpose, that clearly indicates the action to be taken and the reason therefore" [JP 1-02, 2008].

Process: "A series of actions or operations conducing to an end" [Mish, 1994: 929].

Synthesis: "The composition or combination of parts or elements so as to form a whole" [Mish, 1994: 1197].

System: "A set of components (subsystems, segments) acting together to achieve a set of common objectives via the accomplishment of a set of tasks" [Buede, 2000: 38].

Task: An action or activity (derived from an analysis of the mission and concept of operations) assigned to resource to provide a capability [after CJCSM 3400.04D, 2005: Enclosure A, 6].

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EXECUTIVE SUMMARY

Command and control (C2) is an enigma that has been studied by military leaders and warfare analysts for hundreds of years. As a result of the numerous definitions and concepts of C2 throughout history, the design of a C2 system is a daunting challenge to the systems engineer, whose duties include eliciting the operational needs of stakeholders; identifying appropriate system requirements; developing a systems architecture from which specialized engineers can design and build the applicable configurable items; and integrating such configurable items to produce a system that meets the needs of the stakeholders. Adding to the challenge is the understanding and integration of new operational concepts identified by stakeholders as necessary to meet their operational needs. Network-Centric Warfare (NCW) is one such operational concept that has implications on the design and development of C2 systems.

There has been much work conducted to date to enable NCW by networking combat and information systems and by removing the “stove-pipes” of legacy systems. A military C2 system, however, is more than the technology and equipment that comprise it. It also includes the doctrine, organization, training, leadership, personnel, and facilities surrounding the material. It is imperative for the systems engineer to understand the implications of each portion of DOTMLPF on the life-cycle of the system

This thesis dissects the complex engineering process of naval tactical C2 systems in order to identify the points of integration between doctrine and material. The goal was to better understand the influence of doctrine on the overall architecture of the material system in order to ensure developing net-centric systems and net-centric doctrine meet the command and control needs of tactical naval forces.

To begin such study, this thesis presented concepts of command and control developed by military leaders and enthusiasts throughout history. The works of Sun Tzu [1971, 1994], Clausewitz [1984], Van Creveld [1985], and Alberts and Hayes [2006], along with military publications by the U.S. Army [FM 6-0, 2003], U.S. Air Force [AFDD 1, 2003], U.S. Marine Corps [MCDP, 1996], U.S. Navy [NDP 6, 1995], and the

North Atlantic Treaty Organization [NSA, 2008] were reviewed. From the survey and analysis of texts and publications, the author concluded that C2 should be viewed as part of a function-process-system combination.

First, when a specific entity is designated as responsible for the accomplishment of a mission, command is a function by which the responsible entity takes inputs (e.g., mission objective, assigned forces, operating environment, adversary's capabilities, etc.) to produce the desired output (i.e., accomplishment of the mission objective). Second, command and control is the process by which the inputs generate the outputs. Third, a command and control system is the means by which the process is executed. When there is no specific entity designated as responsible for the accomplishment of a mission, the C2 process and the C2 system can still take inputs to produce the desired output. In such a case, inputs to the C2 system such as mission objective may be generated during the command and control process or never generated at all.

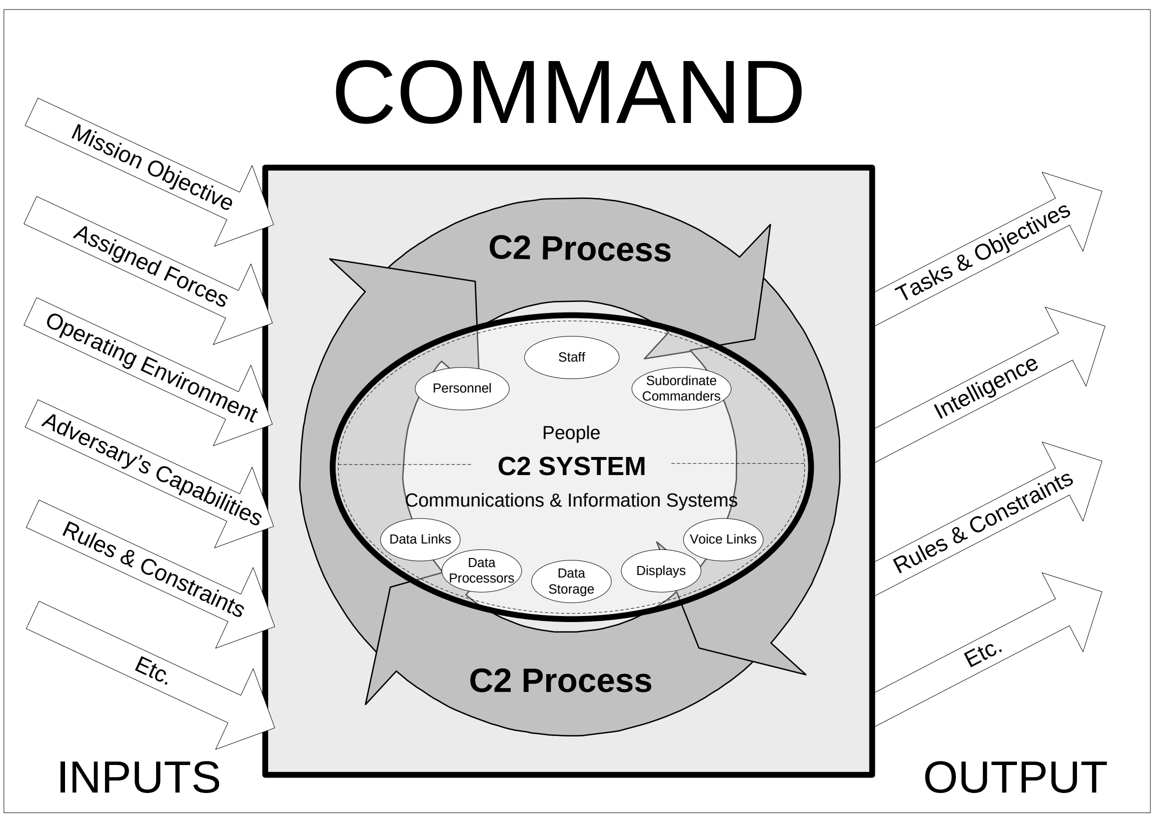

Figure 1. Command and Control: Function-Process-System

Following the survey of texts and publications, the thesis progressed through the system architectural methodology developed by Alexander Levis as presented by Buede [2000] and Levis and Wagenhals [2000]. The methodology begins with the operational concept, moves to the co-development of functional architecture and physical architectures, and concludes with the development of operational architecture.

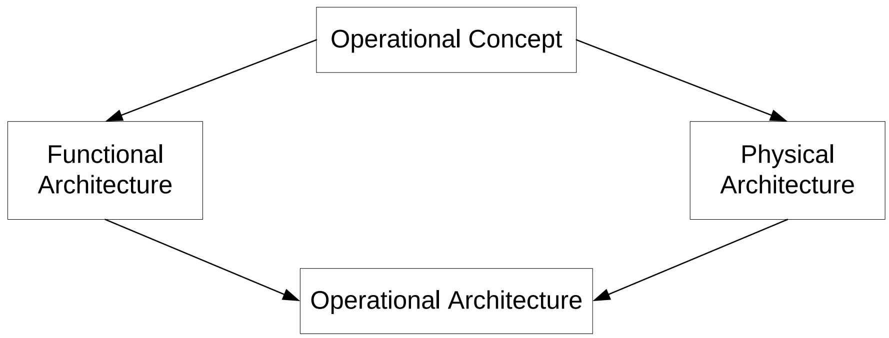

Figure 2. Architecture Development [from Buede, 2000: 20]

The first phase in the architectural process was development of the operational concept. The operational concept was a general vision of the system from the view of stakeholders [Buede, 2000]. It identified the boundaries of, inputs to, outputs from, objectives for, and requirements of the system. First, several employment scenarios describing the operational use of a naval tactical C2 system were developed. Next, incorporating NCW, a refined problem statement was defined:

> A responsive and robust command and control system which connects dispersed forces and enables such forces to self-synchronize and allocate resources to mass effects in order to meet the established intent at the tactical level of war.

An external systems diagram was then developed to define the boundaries of the system and to describe the interactions with the system for applicable stakeholders. The external systems diagram identifies interactions with external systems and the system context (i.e., "A set of entities that can impact the system but cannot be impacted by the system" [Buede, 2000: 38]).

The function-process-system concept of C2 was also used in the development of the external systems diagram, which is evident in the identification of the commander as

an external system. Since the command and control system is the means by which the command and control process executes the function of command for the commander, the commander is not a component of the system.   In addition, the the external systems diagram identifies candidate subsystems and configurable items.

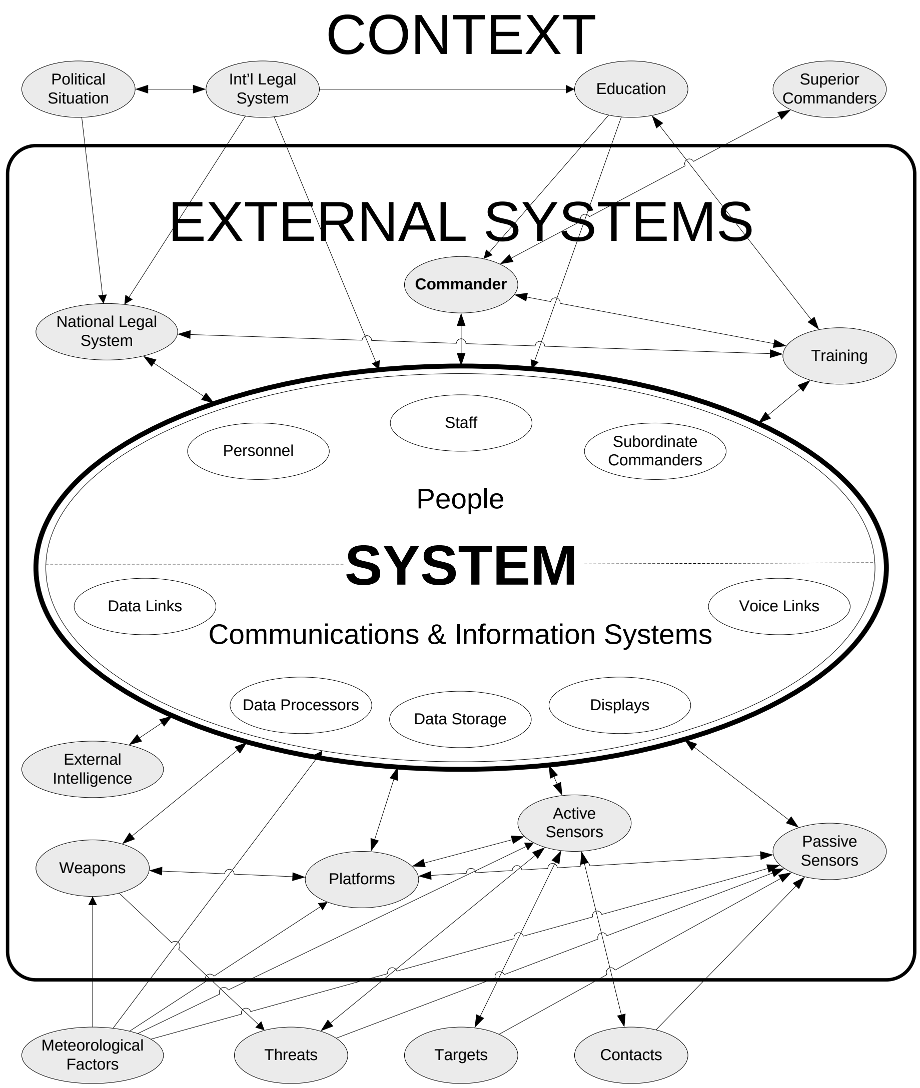

Figure 3. Basic External Systems Diagram

The refined problem statement, again in conjunction with the function-process-system concept of C2, guided the development of a system objectives hierarchy. The purpose of the systems objectives hierarchy was to organize the system's objectives from the view of applicable stakeholders. The development of the systems objectives

hierarchy also included the identification of Measures of Merit (MoM) by which different potential designs of the C2 system could be compared. Completion of the system objectives hierarchy marked the conclusion of the operational concept phase.

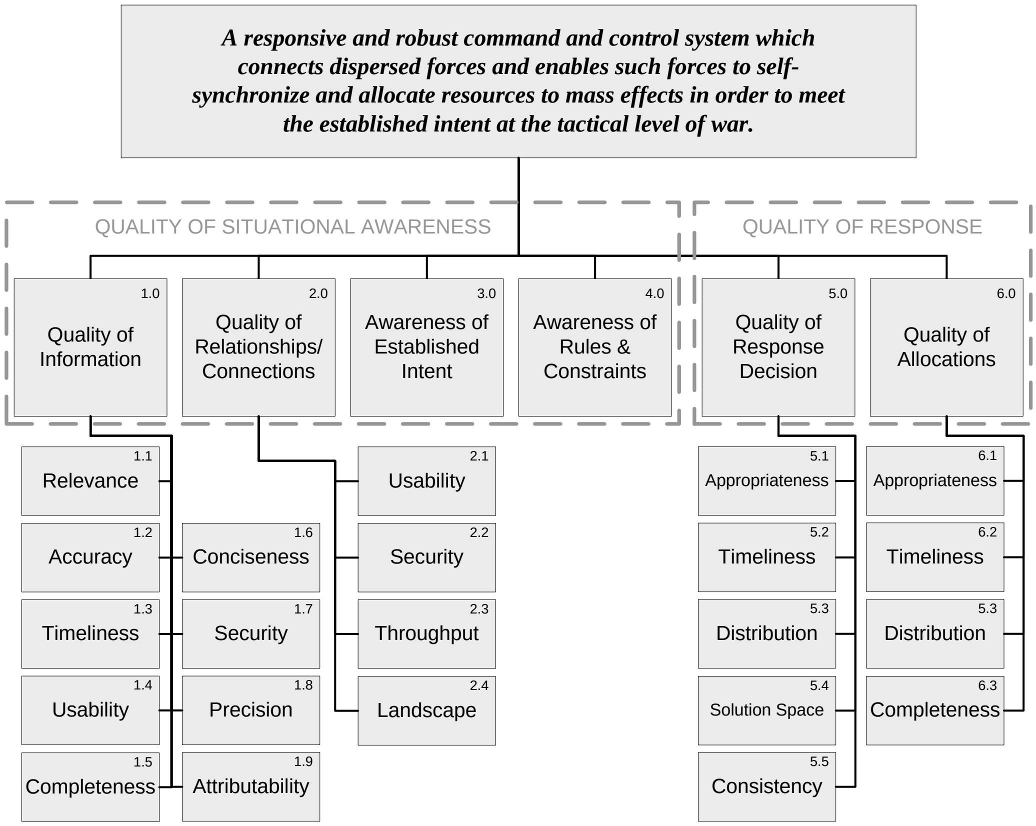

Figure 4. System Objectives Hierarchy

The second phase in the architectural process was the co-development of functional and physical architectures. The purpose of the functional architecture was to describe what the system was to do with the identified inputs to produce the desired outputs. The first step, which was based on the review of texts and publications concerning the concept of C2, was the development of a functional hierarchy. Six top-level functions which a C2 system performs were identified: *Transport Information*, *Process Information*, *Store Information*, *Present Information*, *Generate Response Options*, and *Select Response Options*. These six functions were then decomposed into a hierarchy of sub-functions which were then assigned to different resources identified in the physical architecture to form the operational architecture.

The next step of the functional architecture was to detail the relationships between the inputs and outputs of the system (i.e., describe the sequence of functions converting an input into an output). IDEF0 was selected as the method to detail these relationships. The relationships of the top-level functions are presented in Figure 5.

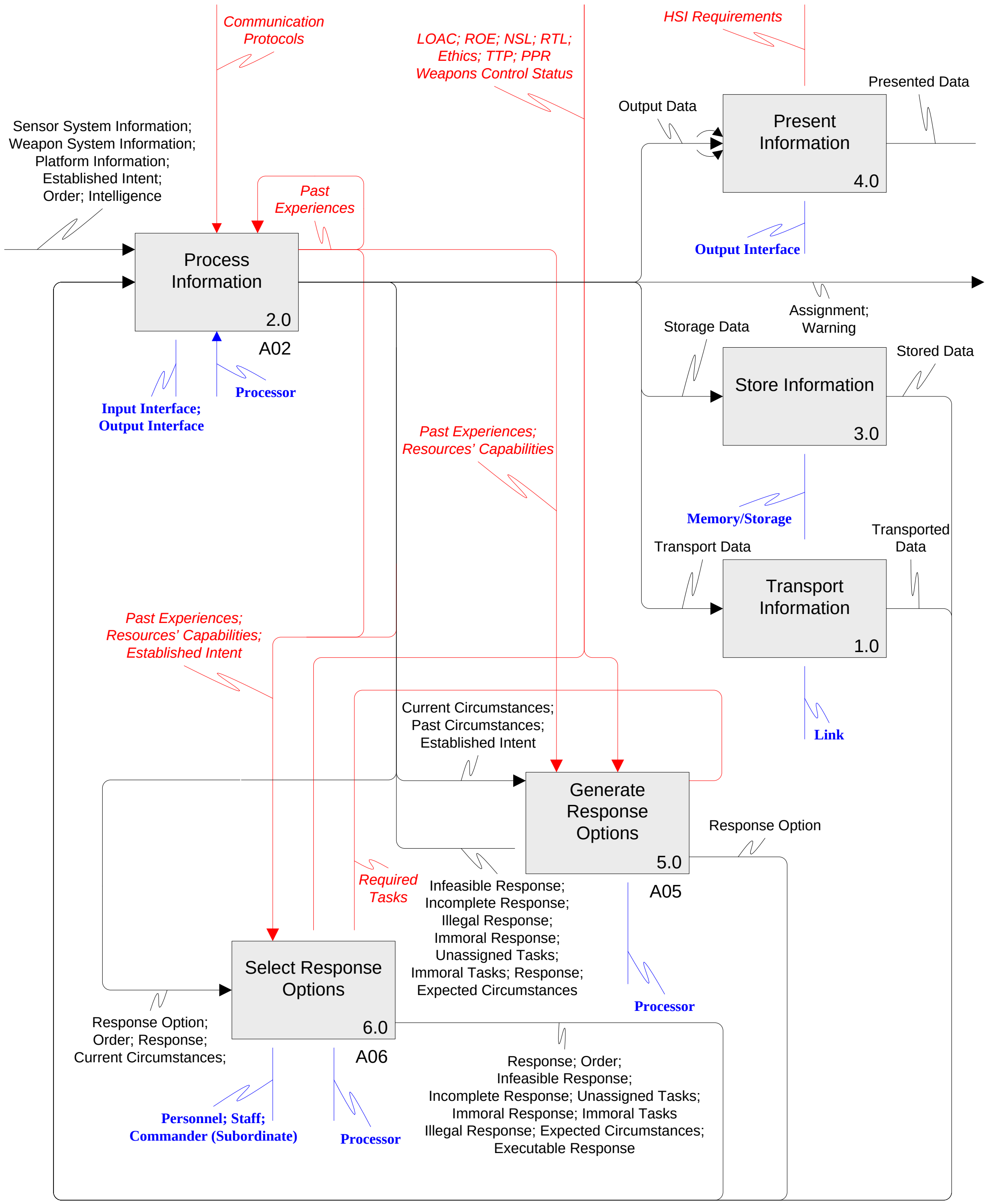

Figure 5. Relationship Diagram – A0

The purpose of the physical architecture was to describe the resources that comprised the system, with resources for every function identified in the functional architecture [Buede, 2000: 215-216]. In addition, the physical architecture described procedures by which the system was used [Buede, 2000: 218] and controls on the system. Generic components, procedures, and controls are also presented above in Figure 5. The final step of the physical architecture was development of instantiated physical architectures from which two potential alternative designs of the system could be built. Differences between the second and first alternative designs of the C2 system was adoption and implementation of doctrine which moved from decentralized decision and allocation authority to distributed decision and allocation authority. From this point the final phase of the architectural process, development of the operational architecture, began.

The operational architecture provided a description of the system design by incorporating products of the operational concept, functional architecture, and physical architecture. First, functions developed in the functional architecture were allocated to physical components developed in the physical architecture. Again, this is presented in Figure 5. Second, activations and controls of functions were described in a framework of the contact prosecution process, a use of a C2 system identified in the operational concept. The functional flow of a portion of the contact prosecution process, for both alternative designs, was then modeled and simulated using Arena®, version 10.0 to demonstrate the ability of the architecture framework to analyze and compare system designs.

The approach and results of the thesis demonstrated only a portion of the system engineering process (i.e., system architecture phases) focused on a small portion of the command and control problem (i.e., the needs of a Surface Action Group tasked to secure local sea control in traditional operating environments), all at a highly conceptual level. This thesis, however, demonstrated the significant impact of doctrine on each phase of the system architectural process and, subsequently, on the design of C2 systems. NCW is more than a framework to view missions, strategies, tactics, techniques, procedures, and organizations available to a networked force; it effects more than the deployment of a C2

system. This thesis showed how NCW affects the definition, objectives, measures, and functions of the C2 system; design of candidate C2 physical architectures; allocation of functions to selected physical components; and flow of the C2 process. This thesis, its approach, and its conclusions provide future researchers with numerous areas of potential study and can assist in the development and integration of net-centric systems and net-centric doctrine to meet the command and control needs of future tactical naval forces.

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I. INTRODUCTION

A. BACKGROUND

The role of the systems engineer is to elicit the operational needs of the customer; identify appropriate system requirements; develop a system architecture from which specialized engineers can design and build the applicable configurable items; and integrate such configurable items to produce a system which meets the needs of the customer. Systems engineers must be cognizant of every phase in the system's life-cycle. This includes the development, manufacturing, operations, and retirement phases.

Network-Centric Warfare (NCW) is an operational concept the U.S. military has identified to meet its operational needs. NCW has implications on the development of many systems the systems engineer supports, including command and control systems. There has been much work conducted to date to enable NCW by networking combat and information systems and by removing the "stove-pipes" of legacy systems. A military system, however, is more than the technology and equipment which comprise it. It also includes the doctrine, organization, training, leadership, personnel, and facilities surrounding the material. It is imperative for the systems engineer to understand the implications of each portion of DOTMLPF on the life-cycle of the system.

B. PURPOSE

Command and control is an enigma which has been studied by military leaders and warfare analysts for hundreds of years. Joining this study enables the system engineer to design and develop more effective command and control systems. To this study systems engineers bring particular professional expertise, namely the practice of dividing complex problems into as many parts is as necessary to determine the solution and gaining greater understanding of the solution through the study and assembly of the simpler portions of the problem [Descartes, 1850: 61].

This thesis dissects the complex engineering process of naval tactical command and control systems in order to identify the points of integration between doctrine and material. The goal was to better understand the influence of doctrine on the overall

architecture of the material system in order to ensure developing net-centric systems and net-centric doctrine meet the command and control needs of tactical naval forces.

C. RESEARCH QUESTIONS

Questions specifically addressed in the research for this thesis include:

- What are the Measures of Effectiveness (MOE) for naval tactical command and control?
- How does doctrine impact the Measures of Effectiveness?
- How, and where, does doctrine impact the system engineering process for a naval tactical command and control system?

D. BENEFITS OF STUDY

The benefits of this thesis are:

- to facilitate communication between the warfighter and system engineer to enable the integration of the net-centric doctrine written by the warfighter and the net-centric systems developed by the system engineer for the warfighter;
- to provide an example for further research of the implications of organization, training, leadership, personnel, and facilities on the system engineering process;
- to provide frameworks enabling modeling, simulation, and analysis of command and control systems for naval tactical units.

E. SCOPE AND METHODOLOGY

The focus of this thesis was on the interaction of doctrine and material (of DOTMLPF) and their subsequent implications during the architectural phases of the system engineering process. The three primary, conceptual systems engineering life-cycle phases are system definition, system development, and system deployment [Sage & Armstrong, 2000: 49]. The architectural phases of the system engineering process encompass the system definition and the initial portion of system development.

Specifically, this thesis focused on the mission needs of tactical naval units (i.e., Surface Action Group) in traditional operating environments in 10 to 15 years.

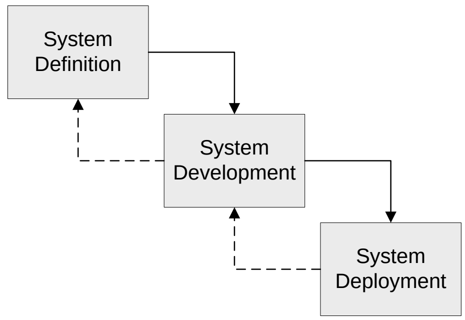

Figure 6. Conceptual Systems Engineering Life-Cycle Phases [from Sage & Armstrong, 2000: 49]

The methodology of architectural phases for this thesis followed the system engineering process developed by Alexander Levis and presented by Buede [2000] and Levis and Wagenhals [2000]. The process starts with the operational concept, moves to the co-development of the functional architecture and the physical architecture, and concludes with the development of the operational architecture. The functional architecture defines what it is the system is required to do. The physical architecture describes the physical resources and procedures for performing the system's functions. The operational architecture integrates the functional and physical architectures through the mapping of the functions to resources.

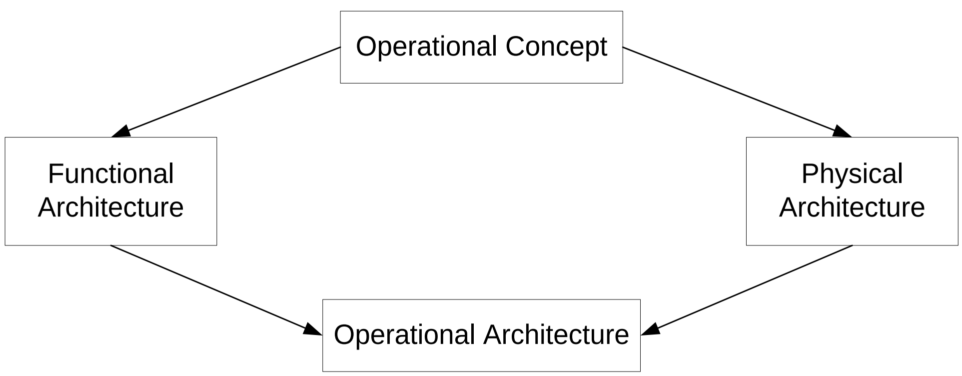

Figure 7. Architecture Development [from Buede, 2000: 20]

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II. OVERVIEW OF COMMAND AND CONTROL

A. INTRODUCTION

Command and control is an enigma which has been studied by military leaders and warfare analysts for hundreds of years. The oldest commonly known writings concerning command and control, Sun Tzu's discussions on the balancing of the five fundamental factors of war, were arguably written nearly 2300 years ago [Sun Tzu, 1971: 11]. Despite the long history of the subject, significant research concerning the principles of command and control only began within the past half-century [Lawson, 1981; Levis & Athans, 1992; Van Creveld, 1985]. With each emerging theory of warfare and every new communications technology, the problems concerning the *design* and *evaluation* of command and control systems become more daunting and complex.

The systems engineer tasked with developing a command and control system can benefit greatly from joining the study and analysis of what exactly is command and control. A crucial task for the system engineer is to continuously communicate with system stakeholders concerning their expectations for the system. Though such communication may be difficult it is necessary for the design of a system which can be used effectively. Researching historical and current works concerning command and control becomes one means of interacting with stakeholders. Additionally, such research can provide the systems engineer with a better understanding of stakeholders' points of view and a common vocabulary for communication. This chapter provides a basic overview of stakeholders' past, present and future concepts of command and control.

B. CONCEPT OF COMMAND AND CONTROL

Some experts propose that a person seeking substantially innovative concepts in command and control is "arguably better off approaching the subject untainted by traditional Command and Control concepts" [Alberts & Hayes, 2006: 31]. Such ignorance can be beneficial, but it can, unfortunately, be a detriment to the systems engineer. Without an understanding of the vocabulary and points of view of the systems' stakeholders, a systems engineer will struggle to have the necessary, effective

communication with the stakeholders. A stakeholder's point of view of command and control is shaped by, among other things, their educational background on the topic as well as their role in interacting with the system. To highlight the similarities and possible differences in the points of view, the following sections present textual and doctrinal concepts of command and control.

1. Textual Concepts of Command and Control

Many historical texts discussing war primarily discussed principles of war as theories and methodologies of conducting warfare. The texts contained limited content specifically correlated to modern concepts of command and control. Significant, published research specifically concerning the principles of command and control only began appearing within the past half-century. This does not mean that a review of historical texts cannot provide the systems engineer with an understanding of stakeholders' points of view concerning command and control systems. Actually, a review of textual concepts of command and control may allude to certain stakeholders' biases and their potential flexibility in system definition. The period of textual writings will range from 2300 years ago to near present day.

The works attributed to Sun Tzu, collected and combined to form the *Art of War* [Sun Tzu, 1971; Sun Tzu, 1994], are a military treatise on military strategy and war. In the presentation of a theory of war and a description of methodologies of warfare, Sun Tzu discusses five factors of warfare. Though translations differ in their analysis of the work, the five factors roughly correlate to 1) moral influence of the ruler, 2) environmental forces, 3) physical attributes of the operating environment, 4) military leadership, and 5) organization and regulation of the military. Sun Tzu asserts that a general must understand these five factors to be successful in war [1994: 167]. Sun Tzu also states "Know the enemy, know yourself; your victory will never be endangered. Know the ground, know the weather; your victory will then be total" [1971: 129]. The author concludes, therefore, that successful command requires an understanding of how the uncontrollable factors (i.e., moral influence of the leader, environmental forces,

and physical attributes of the operating environment) and controllable factors (i.e., military leadership and the organization and regulation of the military) affect both the enemy and oneself.

Clausewitz, writing arguably more than two thousand years after Sun Tzu and being highly influenced by Romanticism [Lynn, 2004: Chapter 6], attributed successful command to his concept of *military genius*. It must be acknowledged, before any specific portion of the work is considered, that Clausewitz's *On War* is a posthumous publication of an unfinished manuscript written in his search for a complete theory of war. Despite the unfinished nature of *On War*, the concept of *military genius* discussed in Chapter Three of Book One is reinforced by ideas presented in Chapter One of Book One, the only portion of the book known to be considered finished by Clausewitz himself [Clausewitz, 1984: 70]. In Chapter One he states, among other things, that a theory of war "must also take the human factor into account, and find room for courage, boldness, even foolhardiness. Consequently, it cannot attain the absolute, or certainty; it must always leave a margin for uncertainty" [p. 86]. Clausewitz's *military genius* is a "harmonious combination" [p. 100] of elements within a commander which, though not necessarily equally distributed, do not conflict with each other. The elements of military genius Clausewitz presents include courage, strength of body and soul, intelligence, coup d'oeil, determination, energy of action, staunchness, endurance, strength of character, and imagination (in particular mental visualization) [pp. 100-112].

Approximately a century and a half after Clausewitz's *On War*, Martin Van Creveld published *Command in War*. Van Creveld's work, just as Sun Tzu's and Clausewitz's, has impacted contemporary thought on command and control and is referenced in numerous publications on the topic, to include works on the design and evaluation of command and control systems. *Command in War*, however, differs from *On War* and *Art of War*, in that it focuses primarily on command, control, and communications in war. Van Creveld uses the term command to include the control and communications. In his introduction on the nature of command Van Creveld states:

> First command must arrange and coordinate everything an army needs to exist - its food supply, its system of military justice, and so on. Second, command enables the army to carry out is proper mission, which is to inflict the maximum amount of death and destruction on the enemy within the shortest possible period of time and at a minimum loss to itself. [p. 6]

Van Creveld's idea of command is not limited to its associated responsibilities. Command, he discusses, can also be viewed by what it does [pp. 6-7]. The processes within command include the collection, storing, retrieval, filtering, classifying, distributing, and displaying of information concerning one's forces, the enemy, and the environment. The process of command also includes the formation of an estimate of the situation, the establishment of objectives, the making of a decision, detailed planning, the drafting of orders, the transmission of orders, the execution of the orders, and the monitoring of the execution with feedback. Additionally, Van Creveld argues that what command does remains constant but, the means by which command is executed changes with time [p. 9].

Command and Control Functions				
Collecting Information	Storing Information	Retrieving Information	Filtering Information	Classifying Information
Distributing Information	Displaying Information	Form Estimate of Situation	Establish Objectives	Make Decision
Plan	Draft Orders	Transmit Orders	Execute Orders	Monitor Order Execution with Feedback

Table 1. Command and Control Functions by Van Creveld [1985]

One of the most recent texts concerning command and control is *Understanding Command and Control* by Alberts and Hayes [2006]. In their work, Alberts and Hayes present a conceptual model of command and control built, not on historical writings of the topic but, on the view of a system tasked with command and control. From this method of study Alberts and Hayes conclude that command and control is a "means toward creating value (e.g., the accomplishment of a mission)" [p. 32]. Additionally,

they conclude that there are seven functions of command and control: establishing intent; determining roles, responsibilities, and relationships; establishing rules and constraint; monitoring and assessing the situation and progress; inspiring, motivating, and engendering trust; training and education; and provisioning [Chapter IV].

Command and Control Functions			
Establish Intent	Define roles, responsibilities and relationships	Establish rules and constraints	Monitor and assess the situation and progress
Inspiring, motivating, and engendering trust	Training and education	Provisioning	

Table 2. Command and Control Functions by Alberts and Hayes [2006]

A review of historical and contemporary texts on command and control in war enables the systems engineer to understand stakeholders' points of view but, it is not sufficient. Review of stakeholders' published doctrine can also improve the systems engineer's understanding of their points of view and enables establishment of a common vocabulary for communication.

2. Doctrinal Concepts of Command and Control

The U.S. Department of Defense (DoD) and foreign militaries are key stakeholders in the life-cycle of military command and control systems. Each organization's point of view of *command and control* is shaped not only by their leadership's education in historical works but also by their operating environments, core capabilities, and force composition. This section provides an overview of *command and control* descriptions and definitions to assist the systems engineer with understanding potential factors influencing stakeholders' views of the system.

The DoD definition of command and control is:

> The exercise of authority and direction by a properly designated commander over assigned and attached forces in the accomplishment of the mission. Command and control functions are performed through an arrangement of personnel, equipment, communications, facilities, and procedures employed by a commander in planning, directing,

> coordinating, and controlling forces and operations in the accomplishment of the mission. [JP 1-02, 2001: 102]

Additionally, the DoD defines a *command and control system* as the "facilities, equipment, communications, procedures, and personnel essential to a commander for planning, directing, and controlling operations of assigned and attached forces pursuant to the missions assigned" [JP 1-02, 2001: 102].

Each military branch of the DoD, despite agreeing to the joint definition above, establishes separate definitions for *command and control* and *command and control system* in their service specific publications. First, the U.S. Army states "*Command and control* is the exercise of authority and direction by a properly designated commander over assigned and attached forces in the accomplishment of a mission. Commanders perform command and control functions through a command and control system" [FM 6-0, 2003: 1-1]. Additionally, the Army defines *command and control system* as "the arrangement of personnel, information management, procedures, and equipment and facilities essential for the commander to conduct operations" [FM 6-0, 2003: Glossary-4].

The U.S. Air Force states:

> *C2 is the exercise of authority and direction by a properly designated commander over assigned and attached forces in the accomplishment of the mission.* C2 includes both the *process* by which the commander decides what action is to be taken and the *systems* that facilitate planning, execution, and monitoring of those actions. [AFDD 1, 2003: 49-50]

The U.S. Marine Corps defines *command and control* as "the means by which a commander recognizes what needs to be done and sees to it that appropriate actions are taken" [MCDP 6, 1996, 37]. Additionally, the U.S. Marine Corps explains "… command and control encompasses all military functions and operations, giving them meaning and harmonizing them into a meaningful whole" [MCDP 6, 1996: 36]. The U.S. Marine Corps also states the "basic elements of our command and control system are people, information, and the command and control support structure" [MCDP 6, 1996: 52].

Finally, the U.S. Navy explains:

> Command and control, therefore, refers both to the process and to the system by which the commander decides what must be done and sees that his decisions are carried out. As defined, the process of command and control includes the planning, directing, coordinating, and controlling of forces and operations, whereas the system of command and control includes the personnel, equipment, communications, facilities, and procedures employed by a commander. [NDP 6, 1995: 6]

In contrast to the U.S. military services, the North Atlantic Treaty Organization (NATO) does not specifically define the term *command and control*. The terms *command, control*, and *command and control system*, however, are defined by the NATO Standardization Agency (NSA). First, NSA defines *command* as “The authority vested in an individual of the armed forces for the direction, coordination, and control of military forces” [NATO Standardization Agency, 2008: 2-C-9]. Second, NSA defines *control* as “That authority exercised by a commander over part of the activities of subordinate organizations, or other organizations not normally under his command, which encompasses the responsibility for implementing orders or directives. All or part of this authority may be transferred or delegated” [NATO Standardization Agency, 2008: 2-C-14]. Finally, NSA defines *command and control system* as “An assembly of equipment, methods and procedures and, if necessary, personnel, that enables commanders and their staffs to exercise command and control” [NATO Standardization Agency, 2008: 2-C-9].

Review of published texts and doctrine provides the systems engineer with an understanding of what command and control is and has been, but does not necessarily enable the systems engineer to understand what command and control will be when command and control systems being designed now become operational. New theories and concepts of warfare, in conjunction with new technologies, all impact the design, use, and evaluation of command and control systems. Two concepts – Network-Centric Warfare and Cooperative Engagement Capability – demonstrate the potential future of command and control and are reviewed in the following sections.

C. CONCEPT OF NETWORK-CENTRIC WARFARE

Network-Centric Warfare (NCW) is a concept of warfare which emerged as a result of the revolution in information and communications technology which occurred in the 1990s. NCW is a framework in which the missions, strategies, tactics, techniques, procedures, and organizations available to a networked force can be viewed [Director, Force Transformation, OSD, 2005: 3; Alberts, Garstka, & Stein, 1999: 87-88]. NCW also provides the networked force a framework in which the rules and constraints of warfare can be reviewed, reevaluated, and possibly redefined. Essentially the inputs to, the outputs from, and the objectives of a command and control system can now be viewed and analyzed with this new concept of warfare.

The concept of NCW consists of a collection of ideas such as geographically dispersed forces, shared awareness, speed of command, self-synchronization, and virtual collaboration [Alberts, Garstka, & Stein, 1999: 87-114]. A discussion of each of these ideas is beyond the scope of this thesis. However, the idea with arguably the greatest impact on this thesis and on the traditionally accepted views of command and control is self-synchronization. Self-synchronization, as discussed by Cebrowski and Garstka [1998], is the ability of the networked force to "organize and synchronize complex warfare activities from the bottom up. The organizing principles are unity of effort, clearly articulated commander's intent, and carefully crafted rules of engagement." Though Cebrowski and Garstka argue that self-synchronization requires unity of effort and commander's intent, Alberts and Hayes contend that "Successfully accomplishing the functions of Command and Control does not necessarily require: Unity of command (an individual in charge); Unity of intent (an intersection of goals); Hierarchical organizations; Explicit control" [2006: 9]. Alberts and Hayes conclude "intent may or may not be (1) explicitly communicated, (2) consciously or formally accepted, or (3) widely shared" via an example of NATO C3, where the first C refers to consultation and where it is common that no supreme authority can determine intent [2006: 37].

D. CONCEPT OF COOPERATIVE ENGAGEMENT CAPABILITY

Cooperative Engagement Capability (CEC) is a networked approach to air defense. "The CEC was developed in response to the need to maintain and extend Fleet air defense against advanced, next-generation threats as well as to complement advances in sensor and weapon systems" [The Cooperative Engagement Capability, 1995: 394]. In practice, CEC connects combat and C2 systems onboard a platform, called a net control unit (NCU), with a Cooperative Engagement Processor (CEP). The CEP is then connected to a Data Distribution System (DDS) onboard the platform which in turn connects with other DDS of other platforms. The CEC process begins when raw sensor, weapon, and C2 data is transmitted from the combat or C2 system to the NCU's CEP. The CEP then transmits the raw data to DDS which in turn transmits the raw data to other connected DDSs onboard other NCUs. Those DDSs then transmit the raw data to their respective CEPs. The CEPs then process the raw data received, either from systems onboard the NCU or from other NCUs, and disseminate the processed data to applicable systems [The Cooperative Engagement Capability, 1995].

The power of CEC is a result of its three principles – Composite Tracking; Precision Cueing; and Coordinated, Cooperative Engagement. With CEC, shared radar data is processed independently on each NCU into composite tracks "with input data appropriately weighted by the measurement accuracy of each sensor input" [The Cooperative Engagement Capability, 1995: 378]. Thus, if sensors onboard a NCU lose a contact, other NCUs can provide the necessary data for tracking. This ability is referred to as Composite Tracking. Additionally, an NCU can initiate actions for onboard systems to secure a local track if the received data concerning a contact meet the established threat requirements [The Cooperative Engagement Capability, 1995: 379]. This capability is referred to as Precision Cueing and enables the local acquisition range to be greatly extended. Finally, an NCU "may fire a missile and guide it to intercept a target, even a maneuvering one, using radar data from another CEC unit even if it never acquires the target with its own radars" [The Cooperative Engagement Capability, 1995: 379]. "Moreover, a coordination doctrine may be activated by the designated NCU for automated engagement recommendations at each unit based on force-level engagement

calculations" [The Cooperative Engagement Capability, 1995: 380]. This capability is referred to as Coordinated, Cooperative Engagement.

CEC has been developed and implemented over a period of several decades for use in air defense, but the concept can easily be extended to other warfare areas such as anti-submarine warfare, surface warfare, and ballistic missile defense. In fact, Perry, Button, Bracken, Sullivan, and Mitchell [2002] present and analyze scenarios concerning the application of CEC to the first and last example warfare areas. Their CEC scenarios highlight the impact of self-synchronization on a military force's effectiveness.

The textual, doctrinal, and near-future concepts reviewed in this and previous sections have presented a small set of the influences on stakeholders' view of command and control. The review, however, has not necessarily brought the reader closer to any true understanding of the topic and may have in fact induced more confusion in the process. Given that an aim of this thesis is to reduce the confusion, it becomes necessary to discuss the view of command and control, no matter how rudimentary, derived from the above review and utilized during research.

E. NAVAL TACTICAL COMMAND AND CONTROL

When a specific entity is designated responsible for the accomplishment of a mission, command is a function by which the responsible entity takes inputs (e.g., mission objective, assigned forces, operating environment, adversary's capabilities) to produce the desired output (e.g., accomplishment of the mission objective). Command and control is the process by which the inputs generate the outputs. A command and control system is the means by which the process is executed. When there is no specific entity designated responsible for the accomplishment of a mission, the command and control process and the command and control system can still take inputs to produce the desired output. In such a case, inputs such as mission objective may be generated during the command and control process or never generated at all.

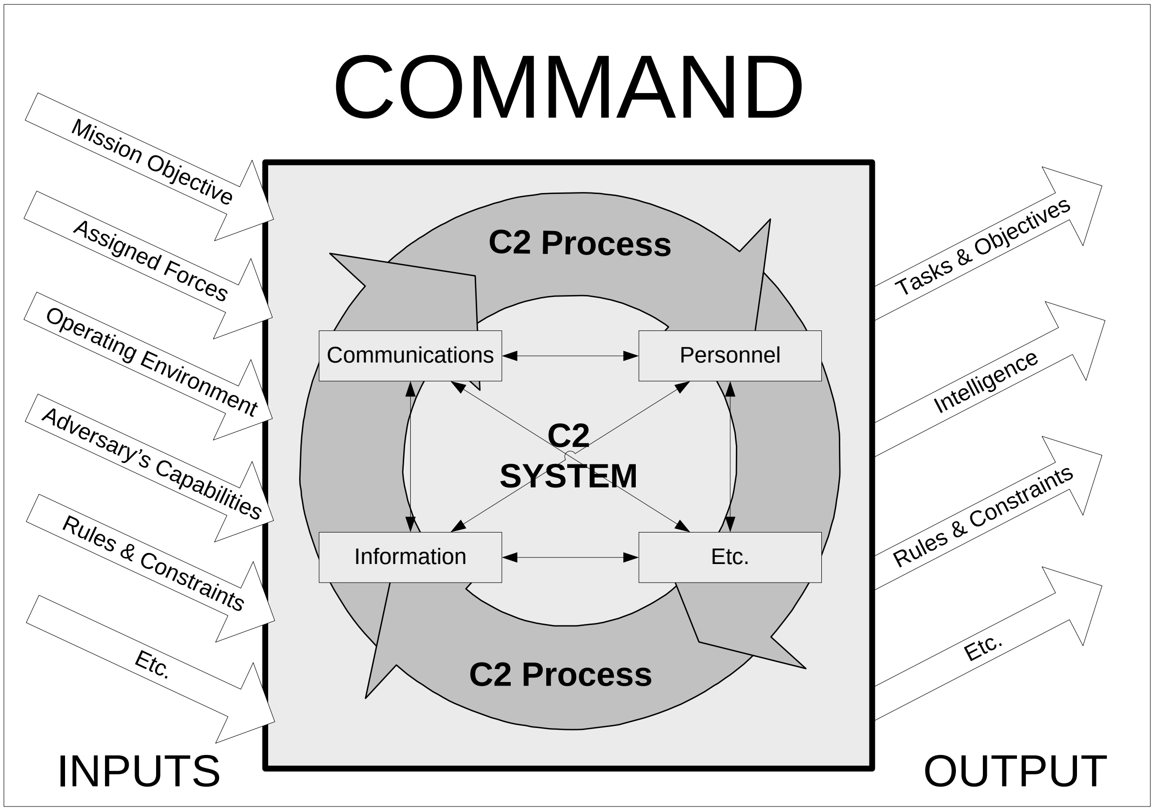

Figure 8. Command and Control: Function-Process-System

Such concept of function-process-system is similar to that presented by Sweeney [2002]. Sweeney contends that command is a function implemented via the command and control process supported by command and control systems. In particular, he describes the command and control process as consisting of people, information, and structure (e.g., organization). Unfortunately, his view of command and control, primarily the process, is inconsistent with common definition and his references. First, a process is "a series of actions or operations conducing to an end" [Mish, 1994: 929]. Of people, information, and organization, only organization could be considered a component of the command and control process and then only if the concept of organization included procedures. Second, Van Creveld argues that what command does remains constant, but the means by which command is executed changes with time [1985: 9]. In other words, the command and control process remains constant but command and control systems are subject to change. People, information, and organization do not remain constant and therefore cannot be components of the command and control process. Third, including

people, information, and organization within the command and control process blatantly contradicts the U.S. Marine Corps [MCDP 6, 1996: 52] and the U.S. Navy [NDP 6, 1995: 6] view that such things are components of the command and control system.

F. CHAPTER SUMMARY

Command and control is an enigma. It is comprised of physical, measurable factors as well as moral, immeasurable factors. It is a function. It is a process. It is a system. Portions of it remain constant throughout time while other portions are constantly subject to change. Successful command and control requires mastery, or at least a deep understanding, of the controllable and uncontrollable forces of war. Ignorance of what command and control is considered to be can be a detriment to the systems engineer.

The purpose of the preceding chapter was to provide a basic overview of stakeholders' past, present, and future concepts of command and control in order to facilitate communication between systems engineers and system stakeholders. The review serves as one means of interaction with stakeholders. The review also provides a common vocabulary for discussion. Though the value of the review may not be apparent to the reader at this time, many of the concepts presented in this chapter will impact the systems engineering process presented in subsequent chapters.

III. OVERVIEW OF SYSTEMS ARCHITECTURE PROCESS

A. INTRODUCTION

The three primary, conceptual systems engineering life-cycle phases are system definition, system development, and system deployment [Sage & Armstrong, 2000: 49]. The architectural phases of the system engineering process encompass the system definition and the initial portion of system development. The methodology of architectural phases for this thesis followed the system engineering process developed by Alexander Levis and presented by Buede [2000] and Levis and Wagenhals [2000]. The process starts with the operational concept, moves to the co-development of the functional architecture and the physical architecture, and concludes with the development of the operational architecture.

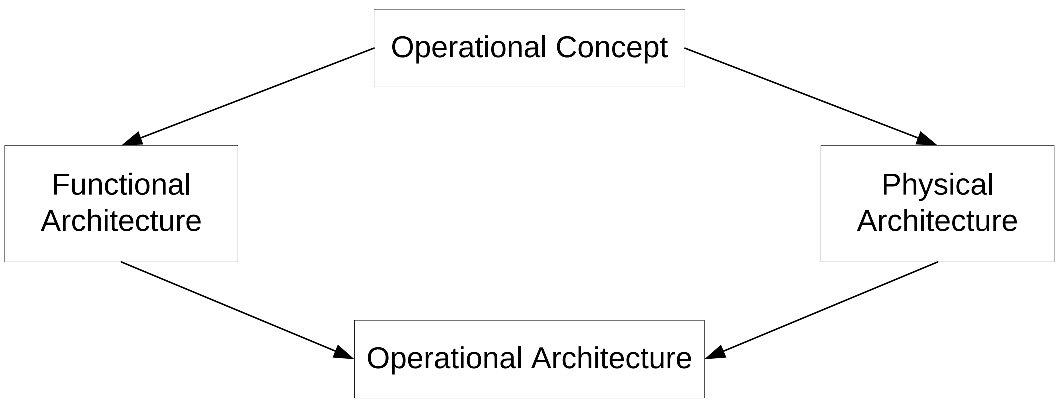

Figure 9. Architecture Development [from Buede, 2000: 20]

B. OPERATIONAL CONCEPT

The operational concept, as presented in Buede [2000], is a general vision of the system from the view of the system's stakeholders and includes a collection of scenarios (both employment and life scenarios); a graphical model describing the system, its boundaries, and its inputs and outputs; objectives for the system; and requirements of the system. To begin the development of the operational concept, a collection of scenarios is generated. The collection of the scenarios should span the entire life cycle of the system and should include all relevant stakeholders during each phase of the system’s life cycle.

Buede [2000: 140] explains that scenarios should include "the relevant inputs to and outputs from the system and the other systems that are responsible for those inputs and outputs."

The initial scenarios developed should be as simple as possible and from the view of the key stakeholder, then expanding the collection to include more stakeholders, complexity of interactions, and phases of the system's life cycle [Buede, 2000: 141]. Generated scenarios should fall into two general categories – life scenarios and employment scenarios. Employment scenarios describe the employment of the system, the operational use of the system. Life scenarios encompass all of the non-operational facets of the system throughout its life-cycle. These two categories are akin to the life and sortie missions developed by Hunger, as presented in Buede [2000], and align with Van Creveld's discussion on the types of responsibilities of command.

> First command must arrange and coordinate everything an army needs to exist - its food supply, its system of military justice, and so on. Second, command enables the army to carry out is proper mission, which is to inflict the maximum amount of death and destruction on the enemy within the shortest possible period of time and at a minimum loss to itself. [Van Creveld, 1985: 6]

In addition to employment and life scenarios, the systems engineer should also develop scenarios describing the validation and acceptance testing of the system throughout its life-cycle.

Development of scenarios is done to assist in defining the *system*, which includes establishing external systems which interact with the *system* and identifying those portions of the context which impact the *system* and the associated external systems. Even if initial scenario development is focused on key stakeholders, the system engineer is still faced with determining the extent of the *system*. Developing scenarios assists in defining the *system* and, to a degree, an understanding of what the *system* is assists in developing the scenarios. A refined problem statement, effective need, or intended design goal of the *system* in question may assist the further development of scenarios.

The collection of developed scenarios and the refined problem statement, when applicable, serve as inputs for the development of the external systems diagram. The

scenarios and problem statement need not be in final form, for the entire systems engineering process is iterative. Input is taken from stakeholders throughout the process and the operational concept is updated accordingly. Just as the refined problem statement assists scenario development by better defining what the system is, so too does the external systems diagram.

The purpose of the external systems diagram is to define the boundaries of the system for all stakeholders of the system. First, a basic external systems diagram is developed based on the work of Levis, as presented by Buede [2000: 124-125]. The basic external systems diagram is composed of three parts - the system, the external system(s), and the context. External systems interact with one or more of the system's subsystems by providing inputs, receiving outputs, or both. The context is the collection of entities which can influence the system but not be influenced by the system.

Details concerning the inputs and outputs of the system as well as the interfaces between parts are not included in the basic external systems diagram. The basic external systems diagram is meant to assist visualization and communication between stakeholders and the systems engineer and to develop a common definition of the system. An example of a basic external systems diagram is presented in Figure 10.

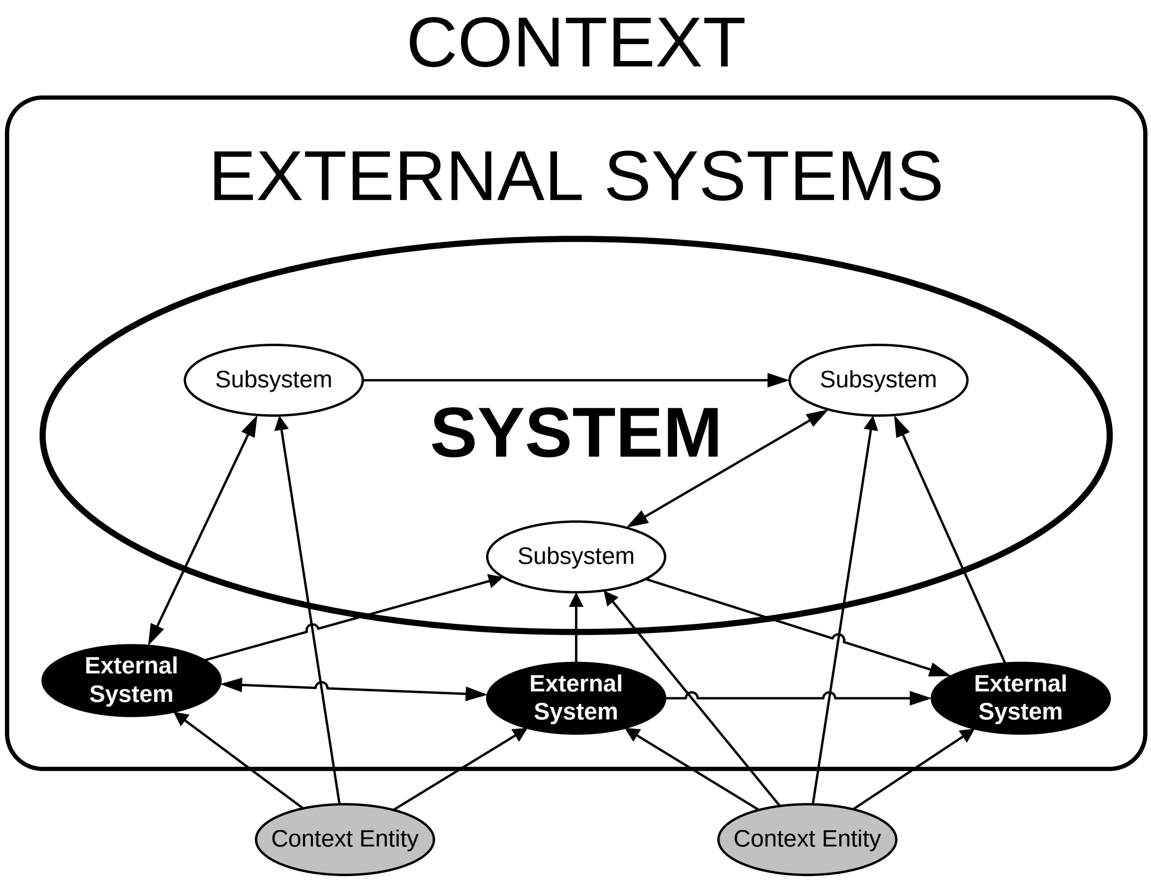

Figure 10. Basic External Systems Diagram [after Buede, 2000: 124]

During scenario development and the drawing of the basic external systems diagram, several key interactions of the system with external systems and contexts are identified but are not detailed. Details concerning such interactions are necessary before an explicit external systems diagram can be completed. There are multiple methods for detailing the interactions of the system with external systems and contexts [Buede, 2000: 141-143; Bruegge and Dutoit, 2004: 59-62]. The system engineer then combines the details of the interaction diagrams, no matter the type chosen, with the basic external systems diagram to form the external systems diagram. An example of an interaction diagram is presented in Figure 11.

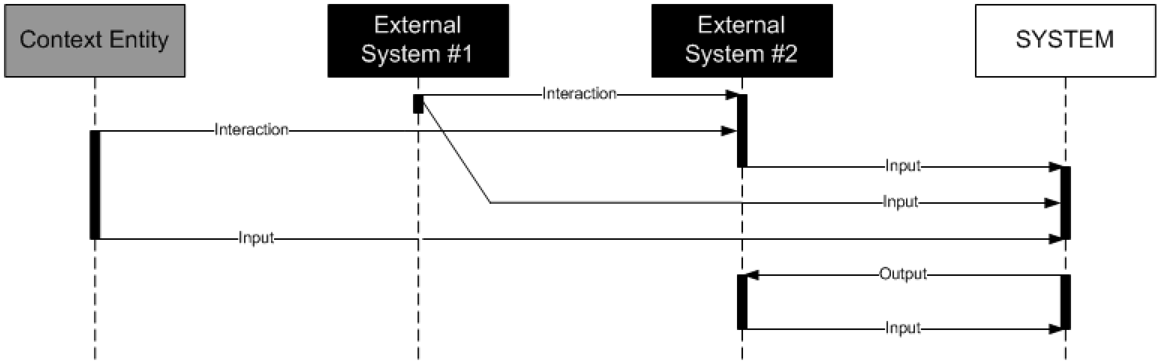

Figure 11. Example Interaction Diagram [after Bruegge & Dutoit, 2004: 60]

From the developed scenarios and refined problem statement, and concurrently with the development of the external systems diagram, the systems engineer develops the systems objectives hierarchy. The purpose of the systems objectives hierarchy is to organize the system's objectives from the view of value to the stakeholders [Buede, 2000: 147]. Care must be taken to understand when a particular objective serves as a means to obtain a higher objective and when its value is fulfilled by lower means objectives. Understanding these interactions enables the system engineer to properly organize the system's objectives to develop the fundamental objective. The process is continued with further inputs from the system's stakeholders concerning the desired values of the pertinent objectives. These inputs enable the system engineer to develop system measures of merit to finalize the objectives hierarchy [Buede, 2000: 146-149].

Requirements are developed with the operational scenarios, external systems diagram, and the system objectives hierarchy providing inputs. Buede [2000] organizes requirements into four groups: input/output requirements, system-wide and technology requirements, trade-off requirements, and qualification requirements. First, each input and output identified during the development of and included in the external systems diagram must have one or more requirements. Rules and constraints pertaining to interface constraints are included as input/output requirements. Second, system-wide and technology requirements pertain "to the system as a whole and not to specific inputs or outputs" [Buede, 2000: 154]. This group of requirements includes technology, suitability, cost, and schedule requirements. Third, trade-off requirements are based solely on the value judgments of stakeholders. Qualification requirements address how

the requirements are observed, verified, validated, and accepted [Buede, 2000: 155-157] and are developed to ensure the system which is built is properly designed and is acceptable.

After verifying the feasibility and testability of the requirements developed, the operational concept is detailed enough to enable the co-development of the functional architecture and the physical architecture. This does not serve as the final form of the operational concept, for it will be repeatedly refined and updated during the developments of the functional, physical, and operational architectures. The operational concept, in whatever form, has described the system from an external view by defining boundaries of the system and identifying inputs to and outputs from the system. The purpose of the next phase of the system architecture process is to describe how the system converts the inputs into the desired outputs and then to define the means by which it does so.

C. FUNCTIONAL ARCHITECTURE

A function is a process that takes inputs and transforms them into outputs [Buede, 2000: 178]. Recall that a system is "a set of components (subsystems, segments) acting together to achieve a set of common objectives via the accomplishment of a set of tasks" [Buede, 2000: 38]. A system, therefore, is defined by 1) its set of objectives and 2) the functions required for it to achieve such set of objectives. The purpose of the functional architecture is to describe what the system is to do with the identified inputs to produces the desired outputs. The functional architecture is developed in an iterative process of five phases. First, the functions of the system are organized into a hierarchy through a combination of decomposition and composition approaches [Buede, 2000: 182-183]. Second, the relationships between the inputs and outputs which were identified during the development of the operational concept are described. The first and second steps are conducted in conjunction with the development of the physical architecture. Third, system stakeholders are solicited for opinions concerning the draft functional decomposition. Fourth, the input and output requirements determined in the operational concept are traced to functions and data elements in the functional architecture. The third

and fourth phases are conducted during the operational architecture development. Finally, as the operational architecture is finalized, fault tolerance and security functions are incorporated with the functional architecture.

The first phase in developing the functional architecture is to develop a hierarchy of the system's functions. This phase is conducted in conjunction with the development of the initial generic physical architecture. To develop the functional hierarchy the system engineer can use a decomposition approach, composition approach, or a combination of both decomposition and composition. Functions of subsystems identified during the development of the physical architecture, or potentially identified in the external systems diagram development, can be synthesized to develop the top-level functions of the system. Top-level functions identified during the development of certain scenarios can be analyzed and decomposed as well. Buede [2000: 183] strongly advises the system engineer to combine both approaches, composition and decomposition, to develop the functional hierarchy.

The second phase in developing the functional architecture is to describe the relationships between inputs and outputs of the system. During the operational concept, interaction diagrams are developed demonstrating the relationship between certain inputs, outputs, and the system. During this phase, these relationships are further detailed to explain the process (i.e., sequence of functions) by which the inputs become the outputs. The system engineer combines the details of the interaction diagrams and the functional hierarchy. There are various methods which the system engineer can utilize to detail or model these relationships. Such methods include functional flow block diagrams, data flow diagrams, N2 charts, or IEDF0 diagrams. An example relationship diagram [after Buede, 2000: Chapter 3; Sage & Armstrong, 2000: 133-134] is presented in Figure 12.

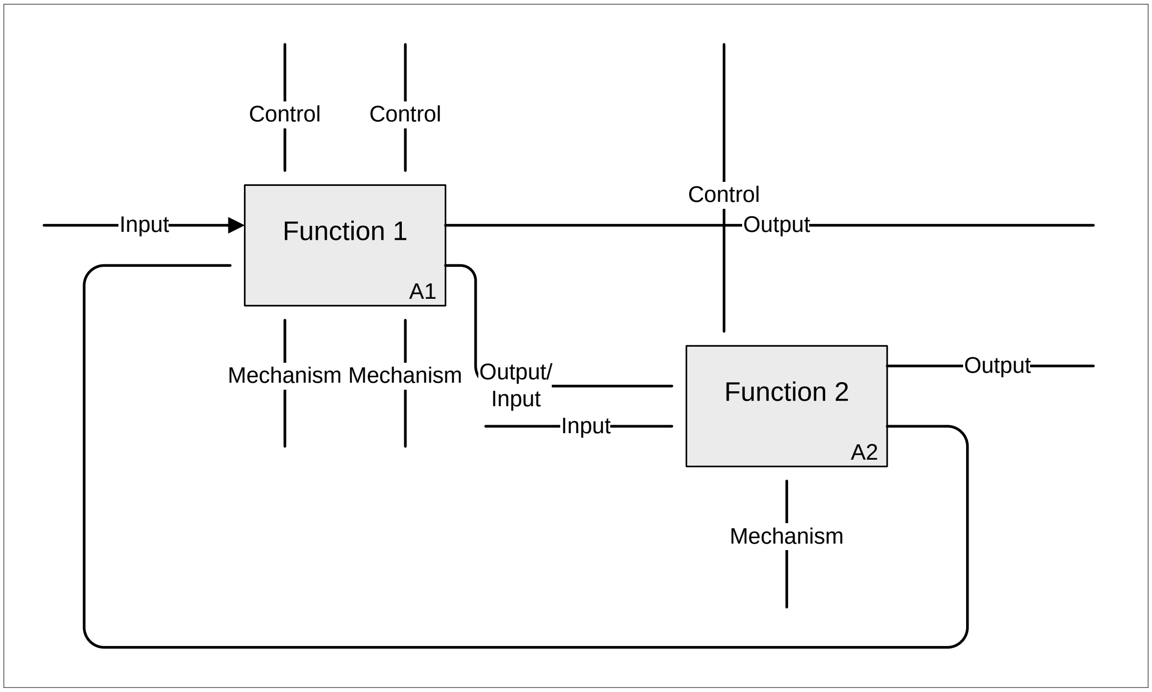

Figure 12. Example Relationship Diagram
[after Buede, 2000: Chapter 3; Sage & Armstrong 2000: 133-134]

The third phase of the functional architecture development is to seek feedback from system stakeholders concerning the functional decomposition. Opinions concerning the generic physical architecture should also be solicited given its simultaneous development with the functional hierarchy. Also during this phase the system engineer should begin the development of the operational architecture [Buede, 2000: 180]. A primary purpose of the stakeholder feedback is to ensure there is not an absence of functionality or a redundancy of functionality in the functional hierarchy.

The fourth phase of the functional architecture development is to trace the input/output requirements. The engineer, through the systems design process, seeks to develop a set of specifications for the development of each subsystem, component, and configurable item. The purpose of this phase is to ensure each of the requirements developed in the operational concept are associated with all of their applicable functions. With the development of the operational architecture, each function's associated requirements will form specifications for the resources identified in the physical architecture.

The final phase of the functional architecture development is the incorporation of fault tolerance and security functions. All systems can have faults which can cause errors leading to failures in the system. However, as Buede [2000: 205] states, functions to detect errors "are typically not part of the initial drafts of the functional architecture because they depend to a significant degree on the physical architecture; as a result these functions are often added once the operational architecture is taking shape." Just as with fault tolerance functions, security functions depend largely on the physical architecture and should be added once the operational architecture has taken shape. Thus the feedback from stakeholders in the third phase and feedback from the operational architecture, which includes fault tolerance and security functions, is what causes the functional architecture development to be iterative. Additionally, fault tolerance and security functions may highlight additional input/output requirements which need to be traced.

D. PHYSICAL ARCHITECTURE

The physical architecture, as presented by Buede [2000], is a hierarchical description of the resources which comprise the system. A purpose of the physical architecture is to provide "resources for every function identified in the functional architecture" [Buede, 2000: 216]. The development of the physical architecture is done in parallel with the functional architecture development. The first phase, then, is to develop a generic physical architecture to partition resources into common categories based on the functions identified in the functional architecture. Once this is accomplished, a set of instantiated physical architectures is developed to assist the development of the operational architecture. As Buede [2000: 218] explains, an instantiated physical architecture is a generic physical architecture with performance characteristics of the system resources included.

To understand the difference between generic and instantiated physical architectures assume the system under consideration is a wrist watch. One generic component of the wrist-watch is a time presentation component. The instantiated physical architecture would include details concerning the time presentation component

such as whether it is an audio presentation or visual display, it is analog or digital, or whether it displayed 12-hour notation or 24-hour notation. The level of detail for the attributes and performance characteristics is pertinent to the system under design.

Once the generic physical components are identified, the next step is to specify attributes and performance characteristics for each of the generic components from which alternative instantiated physical architectures can be designed and selected. There are many techniques for generating numerous physical architecture alternatives. The morphological box technique, suggested by Buede [2000: 222-226], is one method for developing the physical architecture alternatives. "In the two-dimensional version a table is created with columns (or sometimes the rows) pertaining to the generic components of the physical architecture. Then the elements of each column are filled with competing specific instantiations of each component" [Buede, 2000: 223]. An example morphological box for a wrist watch is presented in Table 3.

Wrist Band	**Time of Day Presentation**	**Chronograph Presentation**	**Alarm**	**Power**	**Controls**
Metal Links	Digital	Digital	Audio	Replaceable Battery	Buttons
Metal w/ Clasp	Analog	Analog	Alarm	Solar-Charge Battery	Infra-red
Plastic w/ Clasp	Audio			Motion-Charge Battery	Blue-tooth
Velcro	Braile			Wound Spring	

Table 3. Example Morphological Box – Wrist Watch

In addition to describing the physical resources which comprise the system, the physical architecture also describes the procedures by which the system is used [Buede, 2000, 218]. Similar to the physical components, procedures and controls for the system can have multiple instantiations. When feasible, the system engineer should use creativity techniques such as the morphological box to generate multiple instantiations. Once multiple instantiations are created for all generic physical components and all applicable procedures of the system, the system engineer should develop multiple

alternative physical architectures. These candidate physical architectures will serve as an input for the operational architecture development.

E. OPERATIONAL ARCHITECTURE

The operational architecture provides a description of the system design, incorporating the products of the operational concept, functional architecture, and physical architecture. The major phases of the operational architecture development for this thesis were to allocate functions and requirements to the physical components, describe the activation and control of functions, and to conduct an analysis of the design.

The first step in the development of the operational architecture is the allocation of functions from the functional architecture to components from the physical architecture. The initial phases of this process are conducted in conjunction with the co-development of the functional hierarchy and the generic physical architecture. The collection of relationship diagrams developed for the functional architecture account for this step if generic physical components were identified in the diagrams. If they were not, the systems engineer should accomplish such during the first step of the operational architecture development.

The second step in the development of the operational architecture is to define and analyze functional activation and control structures. The collection of relationship diagrams is refined for each of the alternative physical architectures, incorporating the instantiated physical components and procedures for each. The functional activation and control can be further detailed through the generation table. An example functional activation and control table for the relationship diagram presented in Figure 12. is shown below in Table 4.

Function	Output	Required Inputs	Required Controls
Function 1	Output 1	- Output 3	- Control 2
	Output 2	- Input 1	- Control 1 - Control 2
Function 2	Output 3	- Output 2 - Input 2	- Control 3

Table 4. Example Functional Activation and Control Table

The third step in the development of the operational architecture is to conduct an analysis of the proposed design or set of designs. The system analysis consists of both performance analyses and risk analyses [Buede, 2000: 267]. In many cases these analyses are conducted through modeling and simulation. Once the system analysis is completed, the systems engineer then documents the architectures for approval by stakeholders.

F. CHAPTER SUMMARY

The methodology of architectural phases for this thesis followed the system engineering process developed by Alexander Levis and presented by Buede [2000] and Levis and Wagenhals [2000]. The process starts with the operational concept, moves to the co-development of the functional architecture and the physical architecture, and concludes with the development of the operational architecture.

The operational concept is a general vision of the system from the view of the system's stakeholders. The functional architecture describes what the system is to do with the identified inputs to produce the desired outputs. The physical architecture describes the resources which comprise the system and the associated procedures. Finally, the operational architecture provides a description of the system design, incorporating the products of the operational concept, functional architecture, and physical architecture. The following chapters present the architectural phases conducted for defining and developing a conceptual command and control system for tactical naval units.

IV. OPERATIONAL CONCEPT

A. INTRODUCTION

The operational concept, as presented in Buede [2000], is a general vision of the system from the view of the system's stakeholders and includes a collection of scenarios (both employment and life scenarios); a graphical model describing the system, its boundaries, and its inputs and outputs; objectives for the system; and requirements of the system. Development of the operational concept also produces a common vocabulary to facilitate communication between the systems engineer and stakeholders. During development of the operational concept, the system should be viewed as a black-box. How the system converts inputs to desired outputs and the means by which this is done will be considered during the functional architecture and physical architecture development. This chapter presents the key phases and products within the operational concept development. Appendix A: Scenario Development, Appendix C: External Systems Diagram, and Appendix D: System Objectives provide more details of the operational concept development process outside those presented in this section.

B. SCENARIOS

To begin the development of the operational concept, a collection of scenarios was generated. Scenario development serves as the initial step for stakeholders and engineers to come to a common definition of the system. In practice, the collection of the scenarios should span the entire life cycle of the system and should include all relevant stakeholders during each phase of the system's life cycle. Additionally, the collection of generated scenarios should fall into two general categories—life scenarios and employment scenarios. Employment scenarios describe the operational use of the system. Life scenarios encompass all of the non-operational facets of the system throughout its life-cycle.

Since the focus of this thesis was on the operational employment of a naval tactical command and control system, only employment scenarios were developed. Life scenarios, validation scenarios, and acceptance testing scenarios were not developed.

Potential employment scenarios for naval tactical forces, however, are numerous. Hayes, Krulisch, and White [2008] conducted an analysis of historical and current naval texts and strategies to develop a list of potential objectives for future naval forces. A further decomposition of the analysis was conducted to generate missions for which future naval forces may be employed. These missions, or employment scenarios, include:

1. Secure local sea control
    1.1. Gain and maintain local sea access
        1.1.1. Conduct Mine Sweeping Operations
        1.1.2. Conduct Anti-submarine Operations
    1.2. Deny local sea access
        1.2.1. Conduct Mine Laying Operations
        1.2.2. Conduct undersea, surface, and air patrols of local sea
    1.3. Defeat adversary's fleet
        1.3.1. Provide defense of forces
            1.3.1.1. Maneuver Forces
            1.3.1.2. Prosecute Contacts
            1.3.1.3. Engage Threats
        1.3.2. Conduct attack on adversary's forces
            1.3.2.1. Maneuver Forces
            1.3.2.2. Prosecute Contacts
            1.3.2.3. Engage Targets
                1.3.2.3.1. Engage Planned Targets
                1.3.2.3.2. Engage Dynamic Targets
    1.4. Gain intelligence of the local sea
        1.4.1. Collect information concerning the local sea
            1.4.1.1. Conduct surveillance of the local sea
            1.4.1.2. Conduct reconnaissance of the local sea
        1.4.2. Process/integrate/evaluate/analyze/interpret information to produce intelligence of the local sea
2. Patrol Sea Lines of Communication
3. Seabed Defense
4. Escort
    4.1. Commerce Convoy Escort
    4.2. Military Convoy Escort
5. Provide land defense
    5.1. Maritime Ballistic Missile Defense
    5.2. Mine Defense
6. Conduct land attack
    6.1. Naval Fires Support
    6.2. Strategic Missile Deployment
7. Maritime Interdiction
8. Maritime Security
9. Maritime Domain Awareness

9.1.1. Collect information concerning the global seas which may impact U.S. security, safety, economy, or environment
9.1.1.1. Conduct surveillance of the global seas which may impact U.S. security, safety, economy, or environment
9.1.1.2. Conduct reconnaissance of the global seas which may impact U.S. security, safety, economy, or environment
9.1.2. Process/integrate/evaluate/analyze/interpret information to produce intelligence of the global seas which may impact U.S. security, safety, economy, or environment

10. Humanitarian Assistance and Disaster Response
10.1. Provide heavy lift support
10.2. Provide ship-to-shore lift
10.3. Provide search and rescue support

Given the range of missions future naval tactical forces face, the employment scenario development was further narrowed to encompass only the mission of securing local sea control. The composition of naval tactical forces employed in securing local sea control can vary from operation to operation and has a significant impact on the scope of developed scenarios. A single submarine and a large Carrier Strike Group can both be used to secure local sea control, though the capabilities and methods of both are vastly different. Therefore, the development of the employment scenarios focused on those actions a Surface Action Group (SAG) would conduct in order to secure local sea control.

1. Settings

Once the focus of the scenario development had sufficiently been narrowed, three settings were created. Each of the settings included at least two warfare or operational tasks (air defense, antisubmarine warfare, etc.) which a SAG could be expected to conduct while securing local sea control. The settings served as foundations on which the remaining portions of the scenarios were developed. The three settings are presented in Appendix A: Scenario Development.

2. Scenarios

Once the three settings were finished, scenario development continued by identifying system stakeholders, including interacting systems. A key stakeholder was identified from the initial set of stakeholders which, for all of the settings, was the Officer in Tactical Command (OTC) of the SAG. Initial scenario development was conducted

from the viewpoint of the OTC and included the flow of events as seen by the OTC as well as the pertinent inputs to and outputs from the command and control system. As suggested by Buede [2000: 141], the focus was not on the details of how the system worked but rather how the system was used by or served stakeholders. The process was continued for all of the identified stakeholders and interacting systems to ensure all possible inputs to and outputs from the command and control system were identified. A template for scenario development is shown in Table 5. A collection of the developed scenarios is presented in Appendix A: Scenario Development. A majority of the settings developed included dynamic and time-sensitive targets. Appendix B: Target Engagement presents the engagement process model used during scenario development and the associated terminology.

SCENARIO	
Setting	
Systems & Stakeholders	
Flow of events	
Inputs	
Outputs	
References	

Table 5. Scenario Development Template

3. Refined Problem Statement

The "system" in question was the command and control system for naval forces at the tactical level of war. Since a goal of this thesis was to assist in the integration of net-centric systems and net-centric doctrine to meet the command and control needs of tactical naval forces, a review of publications concerning NCW and Network-Centric Operations (NCO) was conducted to determine potential attributes of the command and control system. From this review, a refined problem statement was developed, which is:

> A responsive and robust command and control system which connects dispersed forces and enables such forces to self-synchronize and allocate resources to mass effects in order to meet the established intent at the tactical level of war.

By *responsive* it is meant the timeliness in which the command and control system can identify changing circumstances (e.g., threats from different functional areas, connectivity of the forces, etc.), determine the impact of the changing circumstances, and enact an appropriate response [after Alberts & Hayes, 2006: 45]. By *robust* it is meant the ability of the command and control system to identify a range of changing circumstances, determine the impact of the changing circumstances, and enact an appropriate response [after JP 6-0, 2006: Ch I, 10]. The traditional view of *dispersed forces*, primarily in early NCW writings, focused on geographically dispersed forces. With the increased discussion in the general press on "cyber-warfare" and information operations, the view of dispersed forces must also include dispersion on the "network" which connects the forces.

Self-synchronization is the ability of a force to "organize and synchronize complex warfare activities from the bottom up" [Cebrowski & Garstka, 1998]. This self-synchronization must also include the ability for the forces to allocate resources at their disposal to *mass effects* to meet the established intent. Massing effects need not require the massing of forces. It must also be noted that the effects emphasized exclude strategic effects (i.e., nuclear weapons).

Established intent is used instead of the traditional "commander's intent" since self-synchronizing forces, which may not be connected with their commander or may have no commander (e.g., coalition forces), may be capable identifying and responding to emerging circumstances which alter the operating environment and their purpose. As Alberts and Hayes [2006: 37] discuss "intent may or may not be (1) explicitly communicated, (2) consciously or formally accepted, or (3) widely shared." Finally, the *tactical level of war* is intended to be the traditional functional warfare areas/missions (e.g., air defense, surface warfare, anti-submarine warfare, strike warfare, maritime interception, etc.). It also re-establishes the exclusion of strategic weapons from the problem.

C. EXTERNAL SYSTEMS DIAGRAM

The initial collection of developed scenarios and the refined problem statement served as inputs for the development of the external systems diagram. The purpose of an external systems diagram is to define the boundaries of the system and describe the interactions with the system for all applicable stakeholders. A basic external systems diagram is developed to assist in the definition of the boundaries of the system and interaction diagrams are developed to describe stakeholder interactions with the system. The products of these steps enable the development of the external systems diagram. Details concerning the development of the external systems diagram are presented in Appendix C: External Systems Diagram.

1. Basic External Systems Diagram

The first step in developing the external systems diagram was the drawing of a basic external systems diagram. The purpose of the basic external systems diagram is to assist visualization and communication between stakeholders and the systems engineer as well as for developing a common definition of the system. The format of the basic external systems diagram used in this thesis is based on the work of Levis, as presented by Buede [2000: 38]. The basic external systems diagram is composed of three parts - the system, the external system(s), and the context.

- **System:** "A set of components (subsystems, segments) acting together to achieve a set of common objectives via the accomplishment of a set of tasks" [Buede, 2000: 38].
- **External Systems:** "A set of entities that interact with the system via the system's external interfaces" [Buede, 2000: 38].
- **Context:** "A set of entities that can impact the system but cannot be impacted by the system" [Buede, 2000: 38].

Details concerning the inputs and outputs of the system as well as the interfaces between parts are described in the interaction diagrams and are therefore not included in the basic external systems diagram.

As in discussed in Chapter II, the author adopted the concept of function-process-system for command and control. First, command is a function by which a responsible entity takes inputs to produce the desired output. Second, command and control is the process by which the inputs generate the outputs. Finally, a command and control system is the means by which the process is executed.

The author posits that people are a component of the command and control system, information is what flows within the system, and organization is a rule or constraint on the system. This version of the concept incorporates ideas of Van Creveld [1985], the U.S. Marine Corps [MCDP 6, 1996], and the U.S. Navy [NDP 6, 1995] among many. This can be seen with the two major component categories - *People* and the *Communications & Information Systems*. The inputs to and outputs from the system, along with the cross-communication between subsystems, are *Information*. The developed basic external systems diagram is presented in Figure 13.

The commander, in this case the OTC, is not considered a part of the command and control system. Since the command and control system is the means by which the command and control process executes the function of command for the commander, the commander is not a component of system. The commander is an external system which affects the command and control process and interacts with the command and control system. If during the command and control process a decision by the commander is needed, such decision is an input to the command and control system. Additional discussion concerning the basic external systems diagram is presented in Appendix C: External Systems Diagram.

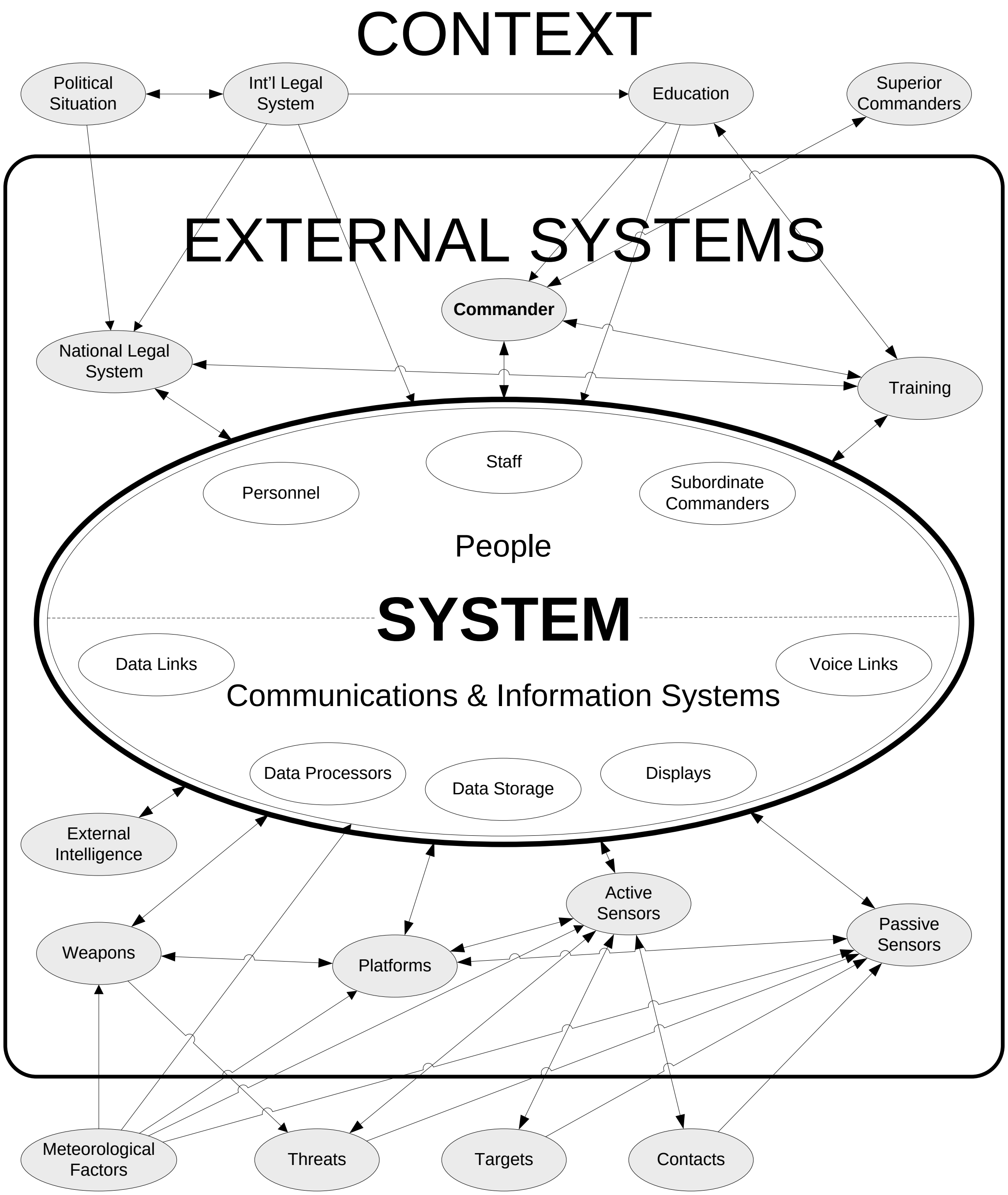

Figure 13. Basic External Systems Diagram

2. Interaction Diagrams

During scenario development and the drawing of the basic external systems diagram, several key interactions of the system with external systems and contexts are identified but are not detailed. Details concerning such interactions are necessary before

an explicit external systems diagram can be completed. There are multiple methods for detailing the interactions of the system with external systems and contexts. Buede [2000: 141-143] presents the input/output trace which provides a sequential representation of one stakeholder's or one external system's interaction with the system. Bruegge and Dutoit [2004: 59-62] present two other types of interaction diagrams, namely sequence diagrams and collaboration diagrams. Sequence diagrams are essentially input/output traces which can depict multiple stakeholders and/or external systems, when necessary. Collaboration diagrams present the interactions numerically (i.e., 1, 2, 3, etc.) rather than graphically.

Due to the complexities of scenarios developed, an expanded input/output trace akin to the sequence diagram presented by Bruegge & Dutoit was used to describe interactions with the system. As described earlier, the basic external systems diagram presented in Figure 13. is a result of the function-process-system concept of command and control adopted by the author. Additionally, the collection of interaction diagrams presented in Appendix C: External Systems Diagram extends this concept and show that *Information* serves as the inputs to and outputs from the system as well as the cross-communication between subsystems. The details described in interaction diagrams are then combined with the basic external systems diagram to form the external systems diagram.

3. External Systems Diagram

The external systems diagram expands the basic external systems diagram to include the inputs and outputs detailed in interaction diagrams. The purpose of the external systems diagram is to model the "interaction of the system with other (external) systems in the relevant contexts, thus providing a definition of the system's boundaries in terms of the system's inputs and outputs" [Buede, 2000: 144]. The external systems diagram is presented in Figure 14.

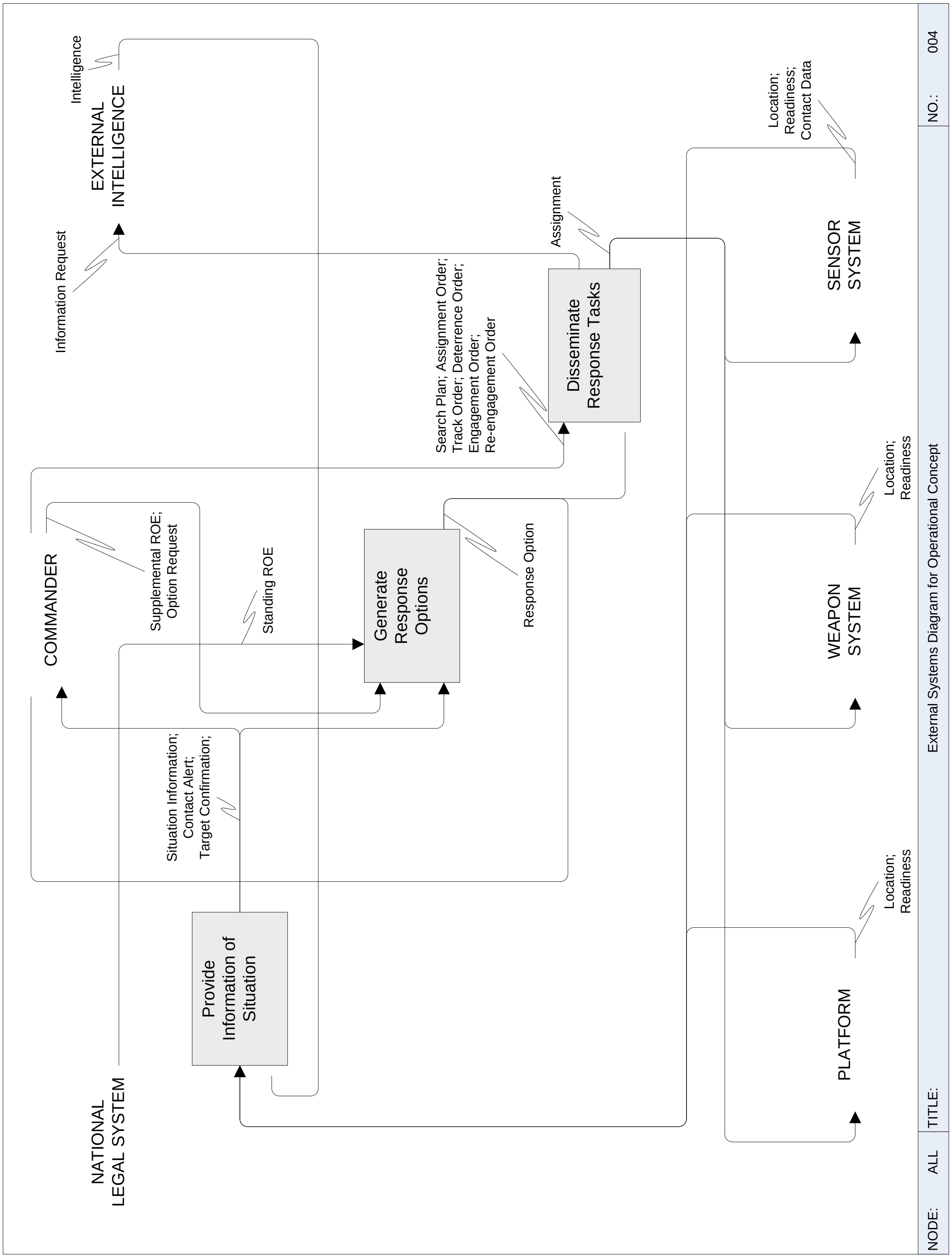

Figure 14. External Systems Diagram

D. SYSTEM OBJECTIVES HIERARCHY

The purpose of the systems objectives hierarchy is to organize the system's objectives from the view of value to the stakeholders [Buede, 2000: 147]. Objectives exist in every phase of the system's life-cycle. Types of objectives can include operational performance, technical performance, operational suitability, cost, schedule, and risk. The focus of this thesis was on the operational employment of a naval tactical command and control system. Subsequently, system objective development focused on operational performance and suitability. Cost, schedule, and risk were not included.

The system objectives development process began with the refined problem statement, developed during scenario development, serving as a guide. Keeney [1992: 56] proposes that "The most obvious way to identify objectives is to engage in a discussion of the decision situation." Since publication research is a form of discussion, as Booth, Colomb and Williams contend [2008: 11], numerous publications concerning measures of effectiveness, operational suitability, C4ISR system capabilities, communications, information theory, and network-centric warfare were reviewed to determine qualities pertinent to a network-centric naval tactical command and control system. In conjunction with the publication review, inputs from stakeholders were solicited to assist the author in developing and organizing the system's objectives and their associated measures of merit (i.e., measures of effectiveness and their associated measures of performance) [Buede, 2000: 146-149].

The system objectives generated were reorganized over several iterations, each time reviewing the refined problem statement to ensure stated properties were accounted for in the objectives hierarchy. The top-level of the system objective hierarchy developed is shown in Figure 15. The full system objective hierarchy and description are presented in Appendix D: System Objectives .

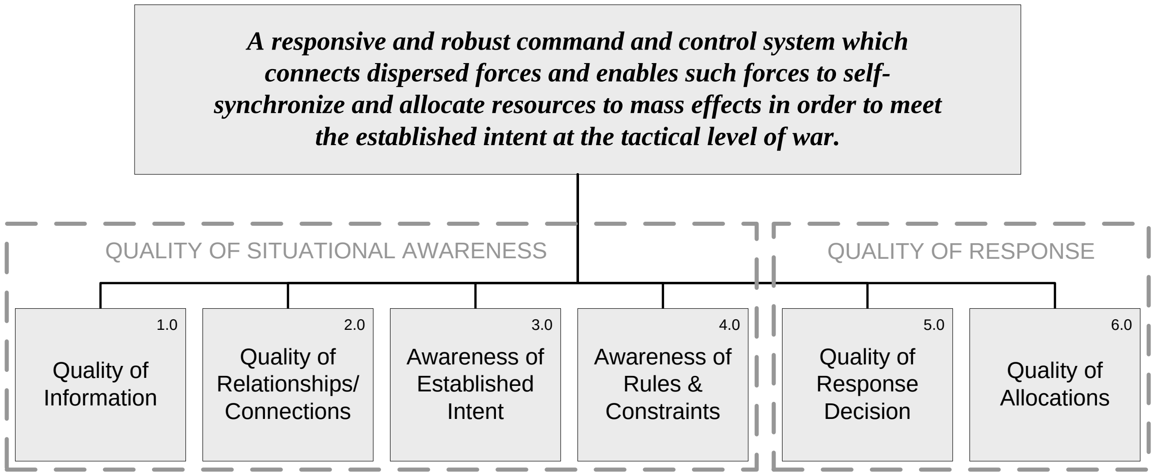

Figure 15. Top-level of System Objectives Hierarchy

Defoe [1993: 7-8] presents seven principles for developing system objectives. Three of Defoe's principles were of particular importance during this phase of the system development. First, the objectives should have "demonstrable links to customer/consumer needs and system requirements" [DeFoe, 1993: 7]. This principle aligns with the *essential* and *operational* attributes identified by Keeney [1992, 82-83]. The publication review, in conjunction with stakeholder solicitation via online discussions and personal communications, served as the methods for accomplishing this principle. Whenever possible, references to the objectives and measures were retained to maintain the traceability of stakeholder need. The stakeholder solicitation also served as the method for accomplishing the second important principle: stakeholders must be allowed to "modify requirements and participate in developing the solution" [Defoe, 1993: 8]. The third important principle is that objectives should be measurable and understandable [DeFoe, 1993: 7, Keeney, 1992: 82, 85]. In alignment with the principle of developing measurable and easily understandable objectives, the concept of Measures of Merit (MoM) [after NATO Research and Technology Organization, 2002: Chapter 5], was adopted.

1. Measures of Merit

Measures of Merit (MoM) are a hierarchy of measures which serve as a base to compare different options. Since the focus of this thesis was on naval tactical forces

tasked with securing local sea control, MoM of the highest level, Measures of Policy Effectiveness (MoPE), were not considered. Additionally, Measures of Force Effectiveness (MoFE) were not considered.

MoFE measure the force's performance in a mission or the extent to which the force meets its objectives. Mission accomplishment is not a measure of the command and control system but rather the force. A command and control system can provide the best possible situational awareness for the commander, the commander can make the best possible decisions, and the command and control system can perfectly convey such decisions to the force but, the mission can still fail if the force executes the decision poorly. To illustrate, consider an air-defense example. A commander, with the assistance of a command and control system, can make the best decision for engaging the air threats based on weapons effectiveness data collected during testing. If, however, the weapons selected fail to perform at the effectiveness level determined in testing, mission failure cannot necessarily be attributed to failure in the command and control system or failure by the commander. The removal of mission accomplishment from the quality measure of a command and control system is a concept further discussed by Alberts and Hayes [2006: Chapter 4].

The MoM levels considered for this thesis included Measures of C2 Effectiveness (MoCE), Measures of Performance (MoP), and Dimensional Parameters (DP). MoCE focus on the impact of C2 systems within the operational context. MoP measure the performance within the system structure. Finally, the lowest level, Dimensional Parameters (DP), measure the properties or characteristics inherent in the physical parts of the C2 systems. For example, the capacity of a particular data link could be a DP whereas the capacity of a network of data links could be a MoP. Continuing, the difference between needed capacity and available capacity of a network of data links in a given situation could be a MoCE. Finally, percentage of targets successfully engaged could be a MoFE. It is a general rule that a measure higher in the MoM hierarchy tends to be more context, task, or mission specific [NATO Research and Technology Organization, 2002: 96].

2. Selected Measures of Merit

Appendix D: System Objectives presents the full system objective hierarchy. Measuring, evaluating, and integrating the results of all of the objectives is important in the development of a command and control system, but is beyond the scope of this thesis. Therefore, with the refined problem statement as a guide, particular MoM were selected as key measures for the remaining phases of the network-centric naval tactical command and control system development. The key MoM selected from the system objectives hierarchy are presented in Table 6. Further discussions concerning the selection process are detailed in Appendix D: System Objectives .

1.2.1	MoP	Number of sources confirming information
1.3.1	MoP	Time between changing circumstances and observation
1.3.2	MoP	Time between the observation and the completion of processing the data into information
1.3.4.4	MoP	Probability of shelf-life is less than time between updates
1.4.1.2	MoP	Percentage of nodes which are capable of viewing information
1.4.2.2	MoP	Percentage of nodes which are capable of acting on information
1.5.2.4	MoP	Percentage of Essential Elements of Information (EEI) met
1.5.2.5	MoP	Percentage of commander's Essential Elements of Friendly Information (EEFI) met
1.8.1.1	DP	Spatial resolution of observation capability
1.8.1.2	DP	Temporal resolution of observation capability
1.9.2	MoP	Number of nodes in the life of the information to which it can be attributed
1.9.1	MoP	Differential between time information is received by a node and when information can be attributed
2.1.1.2	MoP	Percentage of total decision-authorized entities that are available via existing relationships and connections
2.1.1.3	MoP	Percentage of total allocation-authorized entities that are available via existing relationships and connections
2.1.1.4	MoP	Percentage of total action-authorized entities that are available via existing relationships and connections
2.1.2.1.2	MoP	Time between operational failures for the network of connections
2.1.2.2.2	MoP	Probability of operational failure for network of connections
2.3.3.1.2	MoP	Quantity of overflow beyond capacity for the network of relationships and connections
2.4.1.1.4	MoP	Total geographical volume of relationships and connections
2.4.2.1.3	MoP	Median time required to reconfigure relationships and connections to meet changing circumstances and/or necessary responses
2.4.2.2	MoP	Number of possible solutions for required reconfiguration to meet changing circumstances and/or necessary responses
2.4.3.1.4	MoP	Median percentage of nodes which each relationship or connection is capable of connecting with
2.4.4.1.3	MoP	Number of nodes the network of connections are capable of adding
2.4.4.2.7	MoP	Median time required to add all relationships and connections to meet changing circumstances and/or necessary responses
2.4.5.1.3	MoP	Median geographical range nodes can maneuver while maintaining needed relationships or connections
3.2	MoP	Consistency of established intent between forces
4.2	MoP	Consistency of awareness between forces of rules and constraints which are applicable

		to such forces
5.1.2	MoP	Consistency of response with established intent
5.1.4	MoP	Consistency of response with rules and constraints
5.2.1	MoP	Time between receipt of information concerning changing circumstances and acknowledgement of receipt
5.2.2.1	MoP	Time between acknowledgement of receipt of information concerning changing circumstances and response option being developed
5.2.2.2	MoP	Time between response option being developed and response decision
5.2.3	MoP	Time between response decision and order of response execution by decision-authorized entity
5.3.2	MoP	Median number of connections between decision-authorized entity and action-authorized entity
5.3.4	MoP	Percentage of entities connected by existing relationships and connections which are authorized to make a specific decision concerning a specific change in circumstances
5.4.1	MoP	Number of distinct response solutions generated by decision-authorized entities concerning a specific change in circumstances
5.5.2	MoP	Percentage of action-authorized entities with conflicting orders from decision-authorized entities
6.1.3.3	MoP	Percentage of action-authorized entities which are allocated a role or responsibility which they cannot accomplish
6.2.1	MoP	Time between order of response execution by decision-authorized entity and completion of allocations by allocation-authorized entity
6.2.2	MoP	Time between allocation of role or responsibility and commencement of role or responsibility by action-authorized entity
6.3.2	MoP	Median number of connections between allocation-authorized entity and action-authorized entity
6.3.4	MoP	Percentage of entities connected by existing relationships and connections which are authorized to make allocations concerning a specific decision
6.4.2	MoP	Percentage of roles and responsibilities which are required for the specific decision which are not allocated

Table 6. Selected Measures of Merit

E. REQUIREMENTS

Requirements are developed with the operational concept, external systems diagram, and the system objectives hierarchy providing inputs. The following sections discuss each type of requirement and the applicable requirements identified during this thesis.

1. Types of Requirements

Buede [2000] organizes requirements into four groups: input/output requirements, system-wide requirements, trade-off requirements, and qualification requirements. Originating requirements are the collection of these requirements which were developed during the operational concept. The following sections describe each type of requirement.

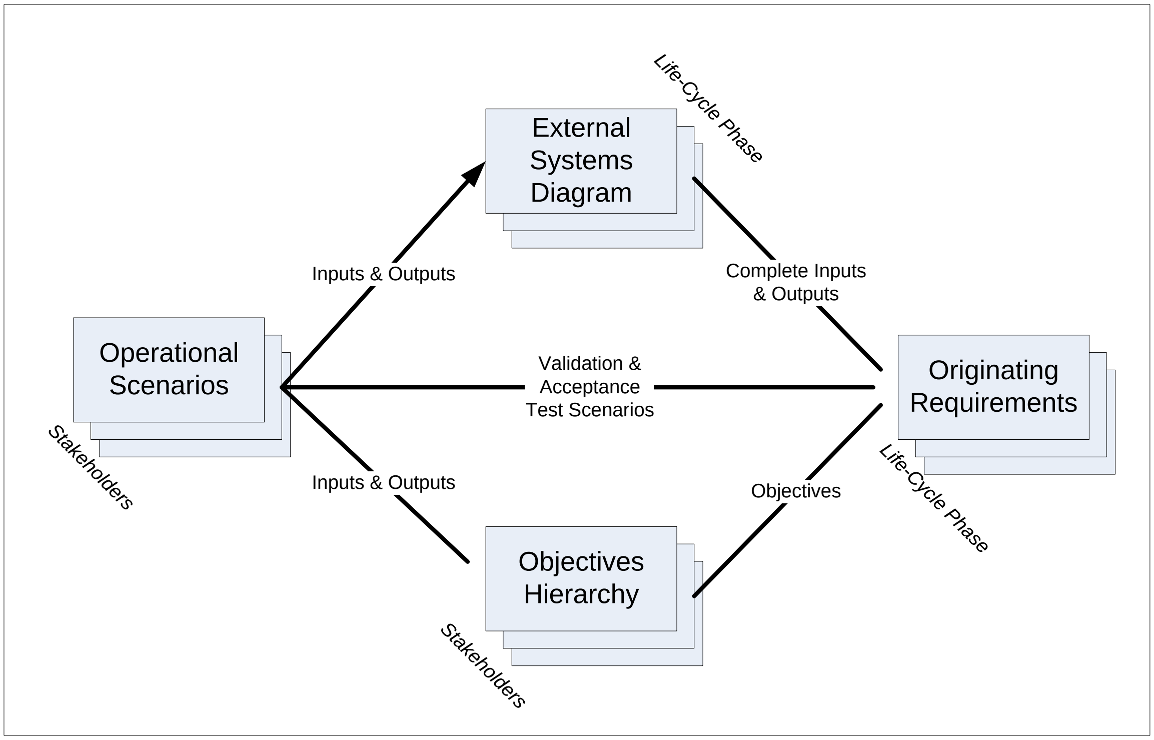

Figure 16. Requirements Development [after Buede, 2000: 159]

a. Input/output Requirements

The external systems diagram is the "primary tool used to support the development of input/output requirements" [Buede, 2000: 153]. Each input and output identified during the development of and included in the external systems diagram must have one or more requirements. For example, a weapon system may require an order with different characteristics than another weapon system. The differences between the orders should then be captured by the output requirements of the command and control system. Rules and constraints for the system, which can be procedural rules or interface constraints, are included as input/output requirements. Rules or constraints which require knowledge of the entire system to determine whether they are met should be included in system-wide and technology requirements. Federal regulations or laws pertaining to the system are an example.

b. System-wide Requirements

System-wide requirements pertain "to the system as a whole and not to specific inputs or outputs" [Buede, 2000: 154]. This group of requirements includes technology, suitability, cost, and schedule requirements. Technology requirements may limit potential solutions for the system design, but are usually included to ensure interoperability or compatibility with external systems [Buede, 2000: 154]. Suitability requirements address such issues as usability, survivability, availability, reliability, maintainability, and testability. Cost and schedule requirements are self-explanatory and are applicable to every phase of the system's life-cycle. For the purposes of this thesis, only technology and suitability requirements were considered.

c. Trade-off Requirements

Trade-off requirements are based solely on the value judgments of stakeholders. Categories of trade-off requirements can include performance trade-offs, cost trade-offs, and cost-performance trade-offs. The techniques for elicitation of trade-off requirements and the set of stakeholders solicited can greatly affect the development of trade-off requirements and subsequently the system. As Buede [2000: 155] warns, "Care must be taken to define a sufficiently large and representative sample of these users."

d. Qualification Requirements

Qualification requirements are developed to ensure the system which is built is properly designed and is acceptable. Qualification requirements must address how the requirements are observed, verified, validated, and accepted [Buede, 2000: 155-157]. Observation refers to how the qualification data is obtained (e.g., testing, analysis, simulation, inspection, or demonstration). Verification refers to how it is determined if the built system complies with the designed system. Validation refers to how it is determined built system complies with the originating requirements. Finally, acceptance refers to how it is determined that the built system is acceptable to the stakeholders.

2. Applicable Requirements

As described in scenario development, and since the focus of this thesis was on the architectural phase of the system engineering process, qualification and trade-off requirements were not developed. Only input/output requirements and system-wide requirements were considered. Requirements generation, however, does not end with the conclusion of the operational concept development. Requirements may, and often times will, become apparent throughout the remaining phases of the system engineering process. Those input/output requirements and system-wide requirements identified during thesis research are shown in Table 7. Given the conceptual nature of this thesis, requirements identified were few and contained little specificity.

Input/Output Requirements	**Reference**
All inputs to the C2 system are in the form of data	Appendix E: Functional Decomposition
All outputs from the C2 system must be in the form of data	Appendix E: Functional Decomposition
System-wide Requirements	**Reference**
N/A	

Table 7. Applicable Requirements

F. CHAPTER SUMMARY

The operational concept is a general vision of the system from the view of the system's stakeholders and is developed to facilitate the co-development of the functional architecture and the physical architecture. Development of the operational concept is not complete until the system engineering process is complete for it is be repeatedly refined and updated during the developments of the functional, physical, and operational architectures. The operational concept describes the system from an external view by defining boundaries of the system and identifying inputs to and outputs from the system. The purpose of the next phases of the system engineering process, functional architecture development and physical architecture development, is to describe how the system converts the inputs into the desired outputs and to define the means by which it does so.

V. FUNCTIONAL ARCHITECTURE

A. INTRODUCTION

A function is a process that takes inputs and transforms them into outputs [Buede, 2000: 178]. Recall that a system is “a set of components (subsystems, segments) acting together to achieve a set of common objectives via the accomplishment of a set of tasks” [Buede, 2000: 38]. A system, therefore, is defined by 1) its set of objectives and 2) the functions required for it to achieve such set of objectives. One purpose of the operational concept is to describe the objectives of the system. The purpose of the functional architecture is to describe what the system is to do with the identified inputs to produces the desired outputs.

The first phase in developing the functional architecture, which was conducted in conjunction with the development of the initial generic physical architecture, was to organize the system’s functions into a hierarchy. The next phase was to detail the relationships between the inputs and outputs of the system (i.e., describe the sequence of functions converting an input into an output). The third phase of the functional architecture development was to seek feedback from system stakeholders concerning the functional decomposition. A primary purpose of the stakeholder feedback is to ensure there was not an absence of functionality or a redundancy of functionality in the functional hierarchy. The fourth and fifth phases of the functional architecture development, tracing of input/output requirements and incorporation of fault tolerance and security functions respectively, were not conducted during this thesis.

This chapter presents the key phases and products derived within the functional architecture development. Appendix E: Functional Decomposition and Appendix F: Input-Output Relationships provide more details of the functional architecture development process outside those presented in this section.

B. FUNCTIONAL HIERARCHY

Developing a hierarchy of the system’s functions was the first phase in developing the functional architecture and was conducted in conjunction with the

development of the initial generic physical architecture. To develop the functional hierarchy the system engineer can use a decomposition approach, composition approach, or a combination of both decomposition and composition. Per the recommendation of Buede [2000: 183] a combination of both approaches was used to develop the functional hierarchy.

As during the development of the operational concept, a publication review was first conducted to provide the author with foundational knowledge of the functions of command and control. This served as a starting point for the composition approach. In addition, comparison of the alternative C2 functions served as the first step of the stakeholder feedback process. Appendix E: Functional Decomposition provides a summary of the publication review. Work conducted during the operational concept development was reviewed as the next step in developing a set of system functions. First, recall the refined problem statement:

> A responsive and robust command and control system which connects dispersed forces and enables such forces to self-synchronize and allocate resources to mass effects in order to meet the established intent at the tactical level of war.

Therefore, three objectives of the command and control system are to *connect dispersed forces*, *enable forces to self-synchronize*, and *enable forces to allocate resources to mass effects*. Second, recall from the discussions concerning the external systems diagram, that the inputs to and outputs from the command and control system are information.

During the development of the operational concept, the system is viewed as a black box [Buede, 2000: 180]. In other words, the operational concept defines the inputs to and outputs from the system but does not describe what the system does to transform the inputs into the outputs. It is during the functional architecture development that the system engineer describes what the system does and in effect shines the light into the black box that is the system [Buede, 2000: 180]. So, from above, if a C2 system takes information as inputs and gives information as outputs, then if the C2 system does nothing else, it at least moves information from one portion of the dispersed force to

another. In effect, it is at least a communication system. Not coincidentally, communication system is a subsystem of the C2 system as detailed in the external systems diagram.

Since communication system is a subsystem of the C2 system, the functions of communications systems are candidates for functions of a C2 system. JP 6-0 [2006: Ch I, 6-8], presents eight functions of communication systems, as delineated in Appendix E: Functional Decomposition – *Acquire Information*, *Process Information*, *Store Information*, *Transport Information*, *Control Other Communications Functions*, *Protect Information*, *Disseminate Information*, and *Present Information*. Dissemination of information is simply the transport of information from the C2 system to a stakeholder or an external system. Acquisition of information is simply the transport of information from a stakeholder or an external system to the C2 system. Therefore, *Acquire Information* and *Disseminate Information* are simply special cases of *Transport Information*.

Control other communication functions is removed as a function of a C2 system for it is implicit in the design of a system. By the mathematical definition, which is the basis of Buede's [2000] definition of a function, a function transforms any element of its domain (i.e., particular input) to one and only one element of its range (i.e., to one and only one particular output). Of course the output from a function may not be the desired output, but by definition of a function the output can be known. This leads one to the topic of fault tolerance. All systems can have faults which can cause errors which can lead to failures in the system. However, as Buede [2000: 205] states, functions to detect errors "are typically not part of the initial drafts of the functional architecture because they depend to a significant degree on the physical architecture; as a result these functions are often added once the operational architecture is taking shape." This is what is meant by implicit in design, for the systems engineer will have a fault tolerance placeholder in their mind when defining system functions. *Protect Information* is removed as a function of a C2 system for similar argument. In essence, protecting information is preventing a system failure of an unwanted entity obtaining or modifying information within the C2 system. In other words, protecting information in a C2 system

is not allowing an interface with an unwanted external system or stakeholder. A fault in the system can cause an error of allowing an unwanted interface. This can lead to a failure of the system with an actual unwanted interface. Security is always an objective of a system where a system is to be used in an environment with an adversary. Just as with fault tolerance functions, security functions depend largely on the physical architecture and should be added once the operational architecture has taken shape. Four functions of communication systems remain as candidates for a C2 system: *Transport Information*, *Process Information*, *Store Information*, and *Present Information.*

Another function of a C2 system, as detailed in Appendix C: External Systems Diagram, is to connect, or link, the phases of the C2 process. A phase of the C2 process can be conducted, partially or wholly, by external systems. For example, most of the conceptual models of the C2 process present a phase akin to *decide*. Given the traditional military view that a decision is made by a commander and that the commander is viewed as an external system for this thesis, the phase of decision is partially fulfilled by an external system. Since a decision requires two options, even if one option is to do nothing, at some time an option must be generated. Of course the option can be generated by the commander; however, this does not *enable forces to self-synchronize*.

Recall that s*elf-synchronization* is the ability of a force to "organize and synchronize complex warfare activities from the bottom up" [Cebrowski & Garstka, 1998]. At this point in defining a C2 system it is not obviously apparent that a C2 system needs to generate options. However, given the increasing tempo of warfare due to automated combat systems and faster weapons, the ability to generate options within the system, instead of aggregating options from external systems such as the commander, may become crucial. In fact, weapon-target pairing is a form of generating options that is currently considered a function of a C2 system. A C2 system need not be the only entity which generates options, but providing the ability should be a function of the system. Following similar reasoning, selecting an option, especially with automated combat systems, should also be a function of a C2 system. In combination, generating and selecting options encompass allocating resources. Generating options includes

determining which available resources can be used, while selecting options includes determining what resources, if any, will be used.

Starting from the refined problem statement, a C2 system should *connect dispersed forces*, *enable forces to self-synchronize*, and *enable forces to allocate resources to mass effects*. To achieve these objectives, a C2 system performs six functions: *Transport Information, Process Information, Store Information, Present Information, Generate Response Options,* and *Select Response Options*. These six functions must be decomposed into a hierarchy of sub-functions which then can be assigned to different resources identified in the physical architecture to form the operational architecture.

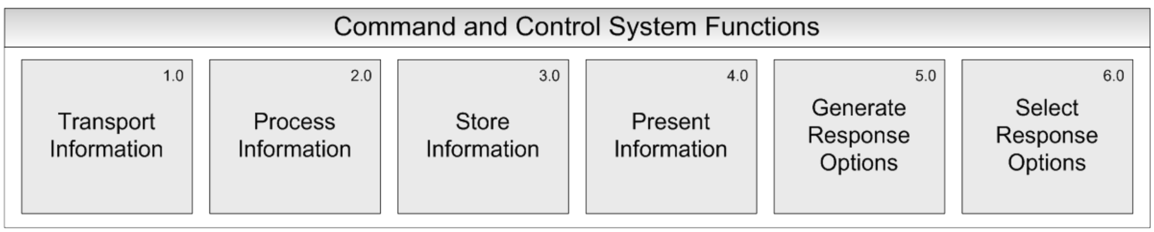

Figure 17. Top-level Command and Control System Functions

The following sections will discuss basic concepts helpful for the functional decomposition, discuss the functional decomposition process, and present the full functional decomposition of the C2 system. The decomposition of some functions incorporate concepts from information theory and human decision making. Appendix E: Functional Decomposition discusses the cognitive hierarchy and certain conceptual models of human decision making which influenced the functional decomposition.

1. Transport Information

The first top-level function, *transport information,* is the moving of information from one place to another. Recall that *transport information* encompasses dissemination of information and acquisition of information. Corresponding to the International Standards Organization (ISO) Open Systems Interconnection (OSI) model, the first level of decomposition for *transport information* relates to the transmission medium.

The second level of decomposition describes the connection type, whether a physical connection or remote connection. Physical connection accounts for those instances when the information traverses through some sort of guide, which physically connects points. Remote addresses those instances when the connected points are not physically connected by a guide. A physical connection requires the two, or more, connected points to either be stationary or move together. Remote allows the two, or more, connected points to move independent of each other. Examples of physical and remote connection methods for each type of transmission medium are presented in the discussion below but are not included in the functional decomposition. The specific methods are, rather, a part of the physical architecture.

The first type of transmission media considered is physical matter, which is further subdivided, as described above, into physical and remote connection. Physical matter transmission media are those instances when the information is stored in matter. An example of a physical connection using physical matter to transmit information is line-pull signals for divers. In such instances divers can communicate with persons, using a predetermined communication scheme, by tugging on a rope or line. Remote connections using physical matter are those instances when the information is stored in matter and such matter is physically transported from place to place. Per the function *store information* discussion below, the storage media can be either human or non-human. A human messenger, a book, a compact disc, and a hard disk drive are all examples of physical matter storage which can contain information and be transported.

The second type of transmission media considered is acoustic. Acoustic is further subdivided into physically connected and remote systems. For example, a sound tube on a ship is a physically connected system while shouting between ships is a remote system.

The third type of transmission media considered is electromagnetic radiation, and, as above, is further divided into physical connection and remote connection. Physical connection accounts for those instances when the electromagnetic radiation traverses through some sort of guide which physically connects points. Examples of physical connection include metal wires, wave guides, or fiber-optic cables. The other methods of electromagnetic transmission account for those instances when the connected points are

not physically connected. These methods include line-of-sight, ionospheric reflection, tropospheric scattering, and satellite communications [Rice & Sammes, 1989: 108]. The decomposition of *transport information* is presented in Figure 18.

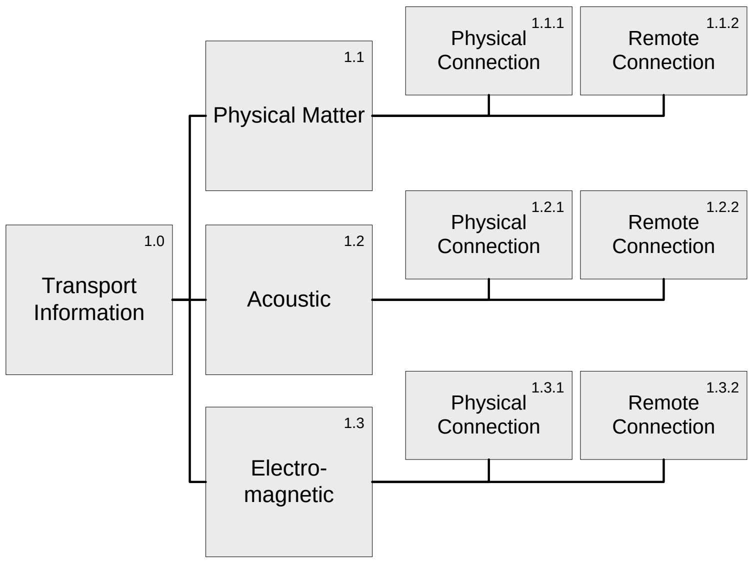

Figure 18.   Functional Decomposition – *Transport Information*

2.   Process Information

The second top-level function is *process information*. The means (i.e., resources) by which the other functions of the C2 system are executed often require information in different forms (i.e., different levels in the cognitive hierarchy) or different formats (i.e., different versions of the same level in the cognitive hierarchy). For example, storing information may require a different form or format of information than presenting information. Therefore, the first three sub-functions of process information entail transforming information into another form or format.

Transport processing entails transforming the information into the data form for transport. It also entails converting the data into a format necessary for transport by a particular resource or set of resources. Similarly, *storage processing* entails transforming information into the data form for storage and converting the data into a format necessary for storage by a particular storage resource or set of resources. *Input Conversion* and *Output Conversion* are concerned with inputs from and outputs to external systems,

respectively. They entail converting the data from the form and format used by the external systems to one useful by the C2 system's components, and vice versa.

Process information, however, includes three other sub-functions. It includes *evaluate data*, which is to determine the accuracy and completeness of the data. *Process information* also includes *analyze information* and *synthesize information.* Analysis is the dividing of information into different parts. Synthesis is the combining of different information to produce new information. The decomposition of *process information* is presented in Figure 19.

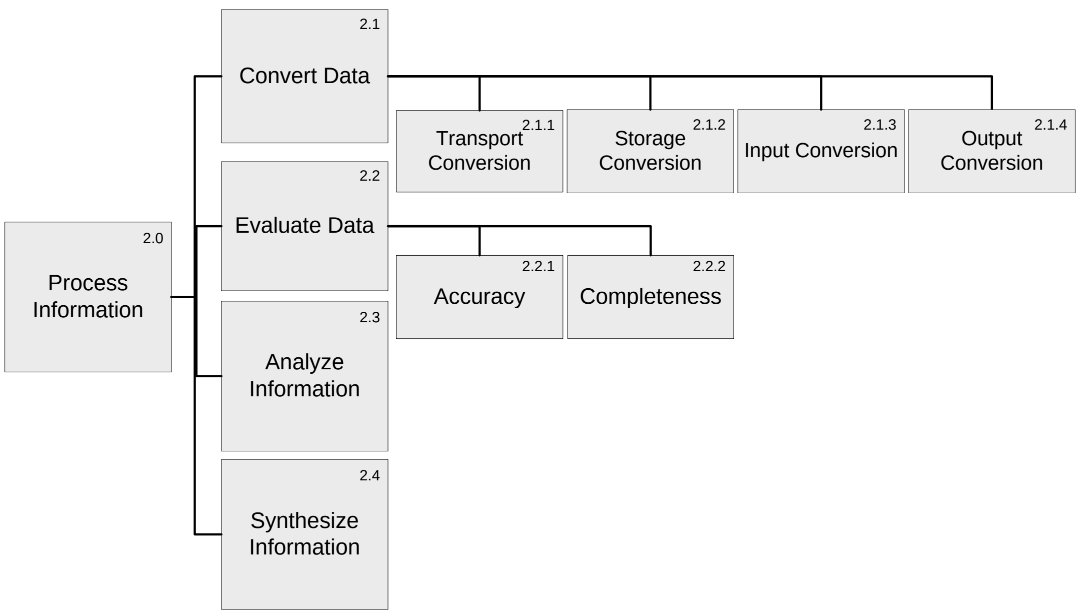

Figure 19. Functional Decomposition – *Process Information*

3. Store Information

Store information is the third top-level function. It is first divided, as alluded to in the discussion of physical transport of information, into *human storage* and *non-human storage*. Human storage is considered the biological composition of a human. If a non-human storage device is located in a human (e.g., a micro-chip embedded in the skin) it is considered non-human storage. *Non-human storage* of information is divided into *short-term storage* and *long-term storage*. *Short-term storage* is the storing of information in a

component external to the processing component for use only within the operating lifetime of the C2 system. Storing of information within the component processing the information is not considered a sub-function of *store information*, but rather *process information*. *Long-term storage* is the storing of information which can be used beyond the operating lifetime of the C2 system.

Human storage, as in *non-human storage*, could be sub-divided into short-term and long-term storage however, it is beyond the scope of this thesis to determine and describe the differences between each. It is for this reason that human and non-human storage was separated in the functional architecture, even though such separation is similar to divisions made in the physical architecture. The decomposition of *store information* is presented in Figure 20.

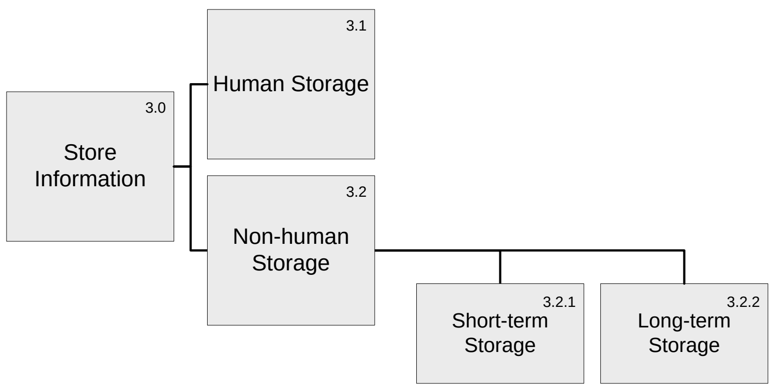

Figure 20. Functional Decomposition – *Store Information*

4. Present Information

The fourth top-level function is *present information*. As discussed previously, dissemination of information is the transport of information from the C2 system to a stakeholder or an external system. *Present information* is portraying information to those stakeholders, external systems, or subsystems which are comprised of humans. In many cases when information is transported to an external system or stakeholder, the information needs to be processed into a form useful to such external system or stakeholder. Human systems, however, differ from non-human systems in their ability to use cognition. Cognition uses more than the processed information to create knowledge

and understanding for the human. Human cognition, as Boyd discusses in his *Orientation* phase of the OODA loop, also uses genetic heritage and cultural traditions as inputs. These inputs to a human stakeholder, external system, or subsystem are beyond the purview of the C2 system. Of course non-human external systems may have inputs beyond the purview of the C2 system, but such systems can be designed to account for such inputs. However, in the cases of genetic heritage and cultural traditions, humans cannot be designed without considerable ethical considerations. The notion of past experiences, from Boyd's *Orientation* phase, was not included since training is a means of establishing a base for past experiences and thus, in effect, designing the human system.

Present information entails portraying information to human stakeholders, external systems, or subsystem for cognition. The next level of decomposition for *present information* follows the methods of input to a human. A human, when viewed as a system, can absorb inputs from an external system in six ways. The first five forms of inputs follow the five traditionally accepted forms of human senses. The sense of motion and pressure are included with the sense of touch. The sixth form of input to a human is direct connection with the brain and nervous system. For ethical reasons, the sixth form of input was not considered as a feasible function for the C2 system. Additionally, olfactory and gustatory inputs were not decomposed. Present information, therefore, is decomposed into *visual presentation*, *aural presentation*, *physical presentation*, *olfactory presentation*, and *gustatory presentation*. Some of these sub-functions were further decomposed by their respective methods. Visual presentation can be in the form of text, symbols, or pictures. The time varying nature is an attribute of these functions. Therefore, video is considered a picture which varies with time. Aural presentation consists of voice and sounds. Physical presentation can be in the form of touch or motion. Finally, olfactory presentation and gustatory presentation were not decomposed because they were presumed to only have one method each for presentation. The decomposition of *present information* is presented in Figure 21.

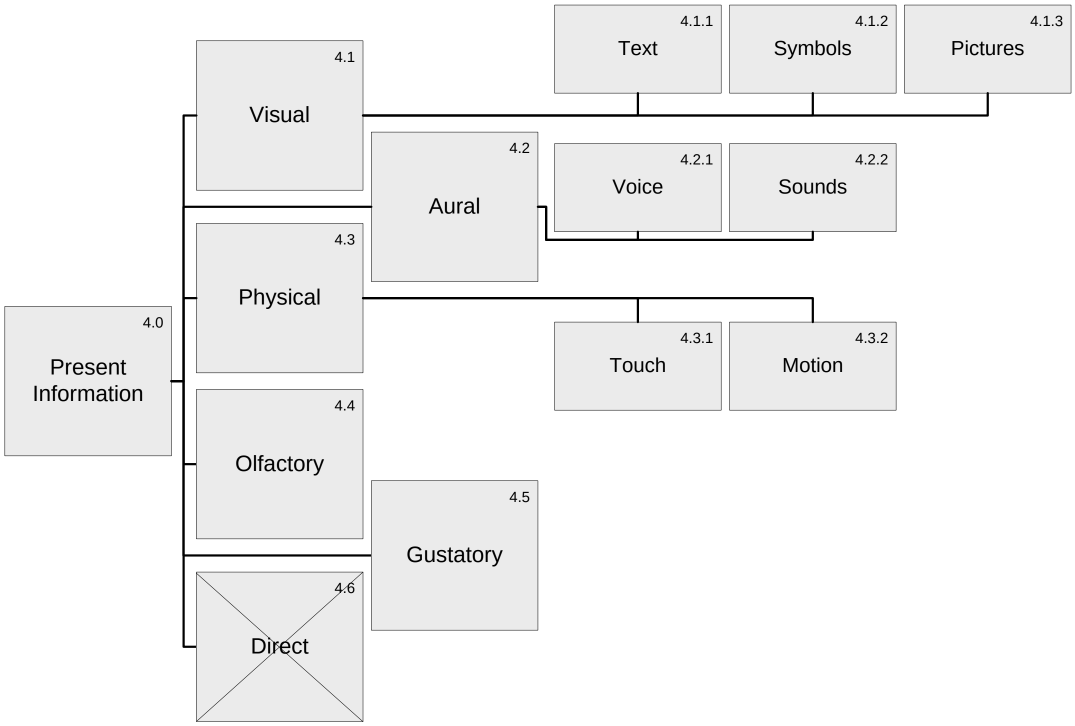

Figure 21. Functional Decomposition – *Present Information*

Present information is concerned with output of the C2 system at the human-system interface. The input to the C2 system at the human-system interface was not neglected in the top-level functions; it was accounted for in *process information*. Of course humans may be better able to portray certain cognitive information using certain methods (e.g., it may be easier to "speak your mind" than to "draw your mind"). However, engineers have designed many standard input interface systems (e.g., keyboards, joysticks, levers, buttons, and microphones) and humans have been trained to convey their cognitive information via these interface systems. A top-level function addressing the inputs from humans could have easily been included similarly to *present information*. However, the notion of standard input interfaces and the human system processing the information into a form which the C2 system can process led the author to view the input at the human-system interface as part of *process information*.

5. Generate Response Options

Generate response options is the fifth top-level function. To better understand *generate response options* and its sub-functions, terminology should be reviewed. First, intent, whether it is an input to the C2 system by the commander or is established by the C2 system, is comprised of a purpose and an objective. A mission is an assignment to a force with a purpose, determined by the intent, and consists of a set of tasks. "The mission establishes the requirement to perform tasks and provides the context for each task performance" [CJCSM 3500.04D, 2005: Enclosure A, 7]. A task is an action or activity assigned to a resource and is determined by analysis of the mission, doctrine, and/or standard operating procedures. Finally, a response option is a set of tasks, with associated resources, which is a solution to achieve the mission objective given the changing circumstances.

First, to *generate response options* the C2 system must *determine changing circumstances.* This sub-function is further divided into *detecting*, *identifying*, *classifying*, and *confirming* the changing circumstances. *Detecting* is discovering differences between current and past or expected circumstances. *Identifying* is recognizing the detected changing circumstances as a specific type. *Classifying* is categorizing the detected changing circumstances by level of danger they present. *Confirming* is verifying the identification and classification of the detected changing circumstances.

Second, the C2 system must *determine the required tasks*. In the cases where the intent or mission is an input to the C2 system certain tasks are specified and certain tasks are implied. Therefore, two sub-functions of *determine required tasks* are to *identify the specified tasks* and *hypothesize implied tasks*. When the intent is established within the C2 system, there is possibly no explicit intent or mission. Therefore, tasks emerge as a result of the changing circumstances. The C2 system must then *hypothesize emergent tasks*. Additionally, when refining response options, the C2 system must also *confirm required tasks*.

Third, since a task is an action or activity assigned to a resource, the C2 system must *identify resources for required tasks.* Finally, *allocate resources for required tasks* is another sub-function. The decomposition of *generate response options* is presented in Figure 22.

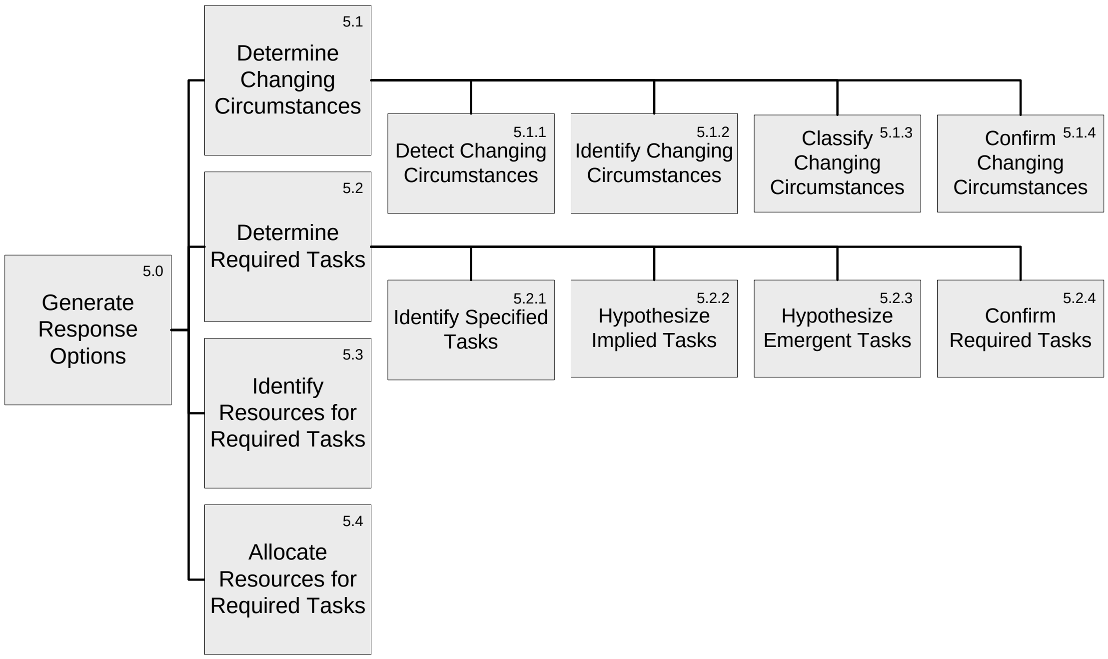

Figure 22. Functional Decomposition – *Generate Response Options*

6. Select Response Options

The sixth and final top-level function is *select response options*, which is comprised of three sub-functions. First, the C2 system should be capable of *evaluating response options* generated. At a minimum, the C2 system should *evaluate feasibility*, *evaluate completeness*, *evaluate legality*, and *estimate effectiveness*. Feasibility addresses whether the resources allocated tasks are capable of accomplishing the task. Completeness addresses whether all of the required tasks of the response option are allocated to resources. Legality addresses whether the required tasks are legal or the resources allocated to a task can legally execute the task. Note a response option need not be feasible, complete, or effective to be selected. A response option in which all tasks are assigned to resources but with at least one task assigned to a resource incapable of accomplishing it is deemed infeasible; it can also be deemed incomplete if such task is

viewed as unassigned. In either view of such response options, it is conceivable that a C2 system may, in some cases, select an infeasible or incomplete response option. Effectiveness is determined through hypothesizing expected circumstances and estimating the expected effects of a response option. Therefore, an infeasible or incomplete response option is likely to be ineffective, but it is also possible for feasible and complete responses to be so as well. Not allowing a C2 system to select an ineffective response option may result in a situation where no response options are available, which may be worse than having poor response options to choose from. In addition, it is assumed that a response option evaluated to be illegal would not be selected.

Second, a C2 system, when containing human components with decision-making authority, should *judge response options*. The purpose of this function is to determine the morality of a specific response option. Finally, to complete the response selection the C2 system must *assign tasks to resources*. The decomposition of *select response options* is presented in Figure 23.

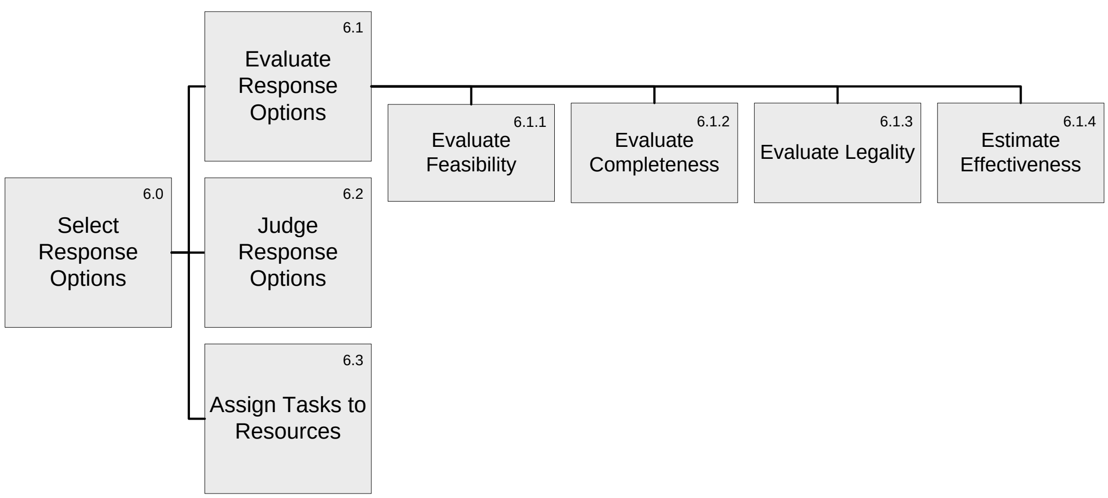

Figure 23.   Functional Decomposition – *Select Response Options*

C.   FULL FUNCTIONAL DECOMPOSITION

All functions and sub-functions discussed in this thesis are collected and presented below in Table 8. Functions which were identified as possible for the C2

system but were deemed infeasible or beyond the bounds of this thesis are listed with strike-through font. Additionally, the top-levels of the functional decomposition are presented in diagram form in Figure 24. Further discussion of the functional decomposition is presented in Appendix E: Functional Decomposition. Fault-tolerance and security functions are not included below since they are not identified until the development of the operational architecture begins to take shape. As discussed previously, comparison of the alternative C2 functions served as the first step of the stakeholder feedback process. In addition, feedback was solicited from C2 researchers and military officers via an online discussion board and personal correspondence.

- 1.0 Transport information
    - 1.1. Physical matter
        - 1.1.1. Physical connection
        - 1.1.2. Remote connection
    - 1.2. Acoustic waves
        - 1.2.1. Physical connection
        - 1.2.2. Remote connection
    - 1.3. Electromagnetic
        - 1.3.1. Physical connection
        - 1.3.2. Remote connection
- 2.0 Process information
    - 2.1. Convert Data
        - 2.1.1. Transport conversion
        - 2.1.2. Storage conversion
        - 2.1.3. Input conversion
        - 2.1.4. Output conversion
    - 2.2. Evaluate data
        - 2.2.1. Evaluate accuracy of data
        - 2.2.2. Evaluate completeness of data
    - 2.3. Analyze information
    - 2.4. Synthesize information
- 3.0 Store information
    - 3.1. Human
    - 3.2. Non-human
        - 3.2.1. Short-term Storage
        - 3.2.2. Long-term Storage
- 4.0 Present information
    - 4.1. Visual
        - 4.1.1. Text
        - 4.1.2. Symbols
        - 4.1.3. Pictures
    - 4.2. Aural

4.2.1. Voice
4.2.2. Sounds
4.3. Physical
4.3.1. Touch
4.3.2. Motion
4.4. Olfactory
4.5. Gustatory
~~4.6. Direct~~
5.0 Generate response options
5.1. Determine changing circumstances
5.1.1. Detect changing circumstances
5.1.1.1. Detect differences between present and past circumstances
5.1.1.2. Detect differences between present and expected circumstances
5.1.2. Identify changing circumstances
5.1.3. Classify changing circumstances
5.1.4. Confirm changing circumstances
5.2. Determine required tasks
5.2.1. Identify specified tasks
5.2.2. Hypothesize implicit tasks
5.2.3. Hypothesize emergent tasks
5.2.4. Confirm required tasks
5.3. Identify resources for required tasks
5.4. Allocate resources for required tasks
6.0 Select response options
6.1. Evaluate response options
6.1.1. Evaluate feasibility of options
6.1.2. Evaluate completeness of options
6.1.3. Evaluate legality of options
6.1.3.1. Compare assigned tasks with law of armed conflict
6.1.3.2. Compare assigned tasks with rules of engagement
6.1.4. Estimate effectiveness of option
6.1.4.1. Hypothesize expected circumstances
6.1.4.2. Estimate measures of effectiveness
6.2. Judge response options
6.3. Assign tasks to resources

Table 8. Functional Decomposition

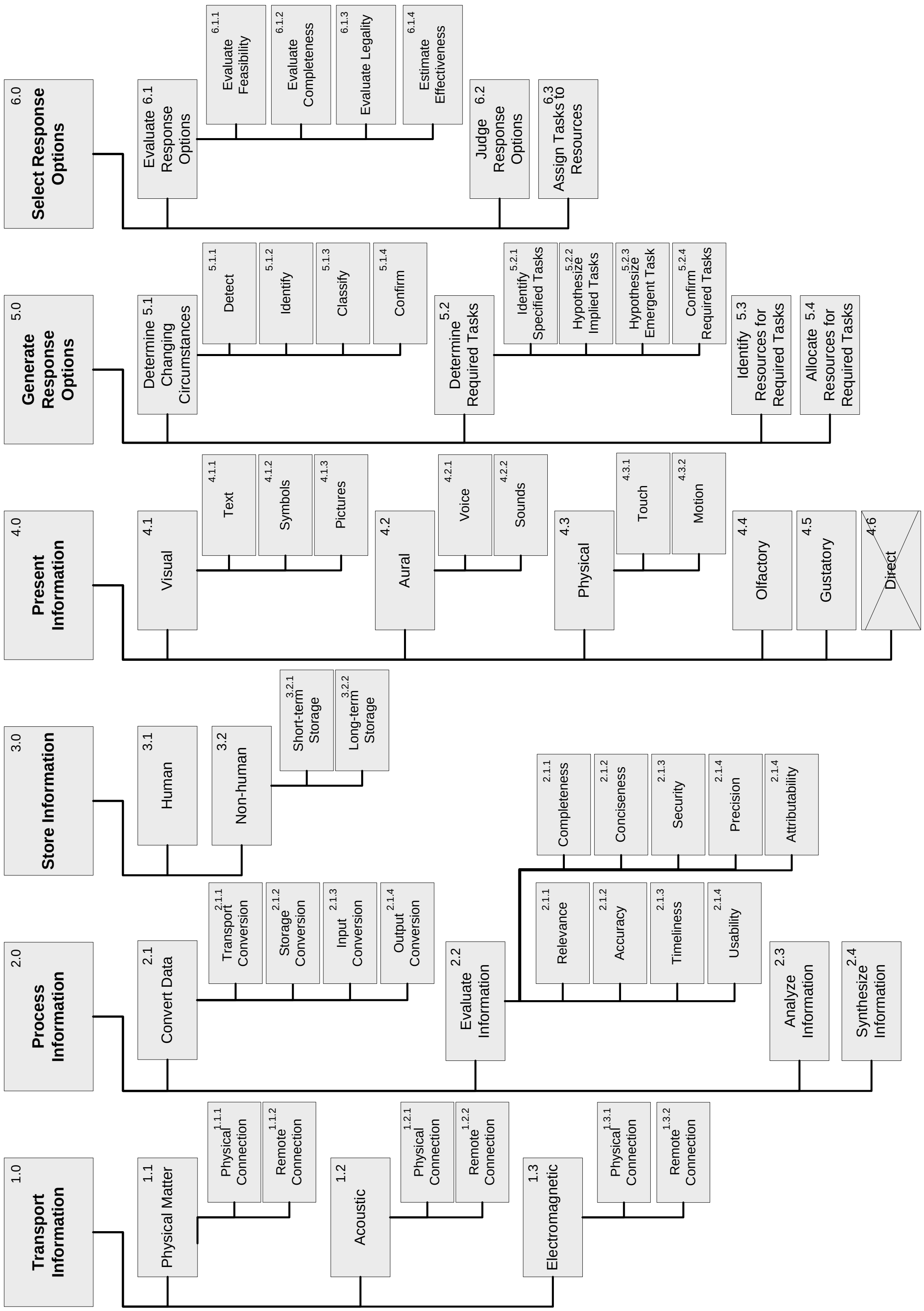

Figure 24. Functional Decomposition – Top Three Levels

D. INPUT/OUTPUT RELATIONSHIPS

After the functional hierarchy was detailed sufficiently, two to four levels as suggested by Buede [2000: 204], the next phase of the functional architecture development was to describe the relationships between inputs and outputs of the system. During the operational concept, interaction diagrams were developed demonstrating the relationship between certain inputs, outputs, and the system. These relationships were further detailed to explain the process (i.e., sequence of functions) by which the inputs become the outputs. In other words, the purpose of this phase was to describe or model the sequence of functions which convert inputs into outputs.

There are multiple methods which the system engineer can utilize to detail these relationships including functional flow block diagrams, data flow diagrams, N2 charts, or IEDF0 diagrams. IDEF0 diagrams were chosen to remain consistent with the work in the operational concept. Figure 25. presents the A-0 diagram, the highest level of the C2 system relationship diagrams; a black-box visualization of the system. It is akin to the external systems diagram and the basic external systems diagram developed in the operational concept. The primary difference, however, is the A-0 IDEF0 diagram does not specify the external systems from which inputs are received and to which outputs are sent. Figure 25. also shows that the A0 diagram presented in Figure 26. that is a sub-diagram of the A-0. The A0 diagram in Figure 26. presents the interactions of the system's top level functions. The A0 diagram is the apex of the collection of relationship diagrams which shine light into the black-box system. The mechanisms shown in both diagrams were determined during the development of the physical architecture, which is discussed in Chapter VI. The remaining collection of developed relationship diagrams is presented in Appendix F: Input-Output Relationships.

The color selection of lines and font in the relationship diagrams is not standard for IDEF0, but were implemented for readability. Red lines and red, italic, sans-serif fonts denote procedures and controls, which will be discussed in the physical architecture. Blue lines and blue, bold, serif fonts denote mechanisms, again which will be discussed in the physical architecture. Black lines and black, sans serif fonts denote

inputs and outputs. In those instances where an output of one function was a control for another function, the line and font was drawn in red.

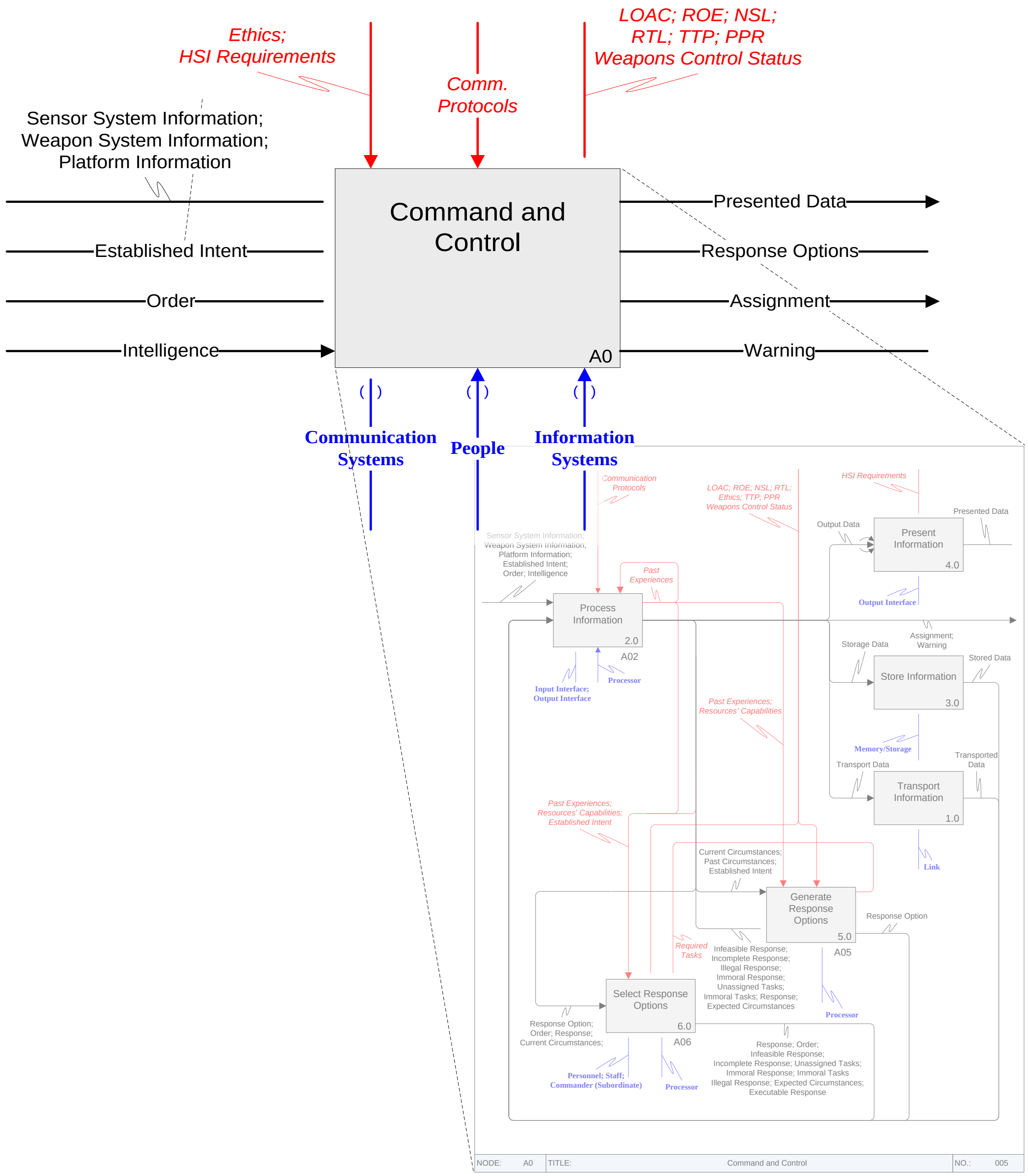

Figure 25. Relationship Diagram – A-0

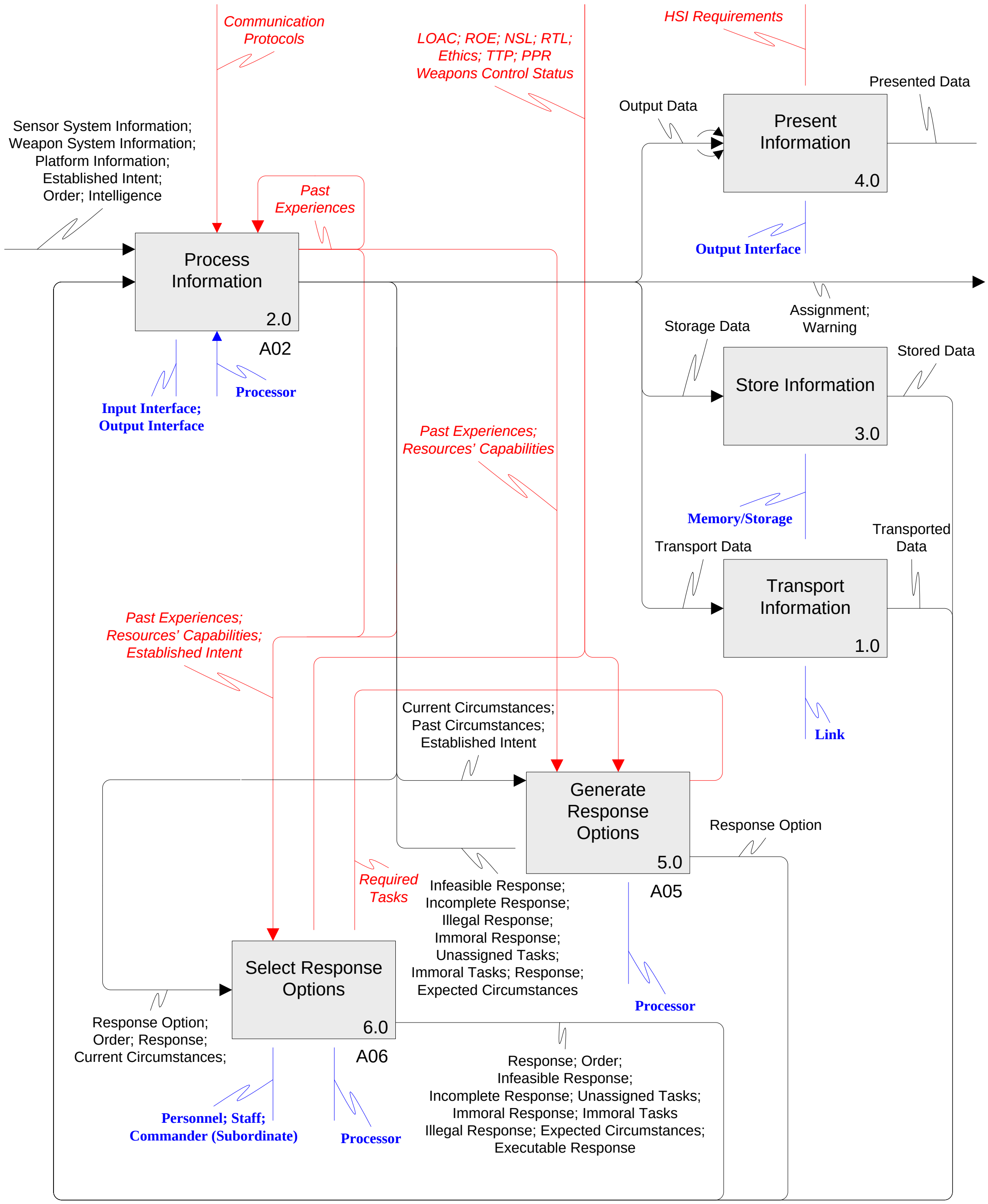

Figure 26. Relationship Diagram – A0

The A0 diagram in Figure 26. presents the interactions of the system's top level functions. The diagram demonstrates the internal process to take inputs to produce desired outputs. First, the C2 system accepts inputs from external sensor systems, weapon systems, platforms, and people (e.g., established intent). The C2 system then

processes the inputs for transport, storage, or presentation. The transported and stored information are then processed to produce information on current and past circumstances. The system then takes current and past circumstances along with established intent, when it is available, to produce a response option. The response option is then processed, transported, and/or stored. If the response option is selected, it becomes a response that is processed, transported, and/or stored once again. From the response, an executable response is created that is processed, transported, and/or stored to finally produce an assignment and/or warning to external systems and people. If the response option was not selected, it would be processed, transported, and/or stored and used as input to generate a new response option.

One key idea demonstrated in the diagram is the centrality of the function *Process Information*. It is the first function of the C2 system for all inputs. In addition, it provides input to all of the other top-level functions. By no means is *Process Information* the only critical function. All of the top-level functions are critical functions of the system. Rather, the systems engineer should realize in developing the physical architecture, that the procedures for and controls on *Process Information* will have substantial impact on all of the sub-functions and the C2 system as a whole.

E. INPUT/OUTPUT REQUIREMENTS TRACE, FAULT TOLERANCE FUNCTIONS, AND SECURITY FUNCTIONS

The final two phases of the functional architecture development are the trace of input/output requirements and the inclusion of fault tolerance and security functions. Given, as discussed in Chapter IV, the limited number and general requirements identified, a trace of input/output requirements was not formally conducted. Additionally, as Buede [2000: 205] discusses, fault tolerance and security functions depend significantly on the physical architecture and are not typically included in the functional architecture until the operational architecture takes form. Given the scope of this thesis and the conceptual nature of the physical and operational architectures, identification and development of fault tolerance and security functions were not conducted.

F. CHAPTER SUMMARY

The purpose of the functional architecture was to describe what the system was to do with the identified inputs to produces the desired outputs. Key phases of the functional architecture development were conducted simultaneously with the development of the physical architecture, as presented in the following chapter. First, the functions of the proposed C2 system were identified and organized into a hierarchy. Second the relationships between inputs and outputs of the system were detailed through relationship diagrams. In addition, informal stakeholder feedback was conducted through a survey of C2 functions and solicitation from C2 researchers and military officers via an online discussion board and personal correspondence. The following chapter presents the physical architecture development process conducted simultaneously with the functional architecture. The products of the physical architecture along with those of the operational concept and functional architecture are incorporated in the operational architecture.

VI. PHYSICAL ARCHITECTURE

A. INTRODUCTION

The purpose of the physical architecture is to describe the resources that comprise the system, with resources for every function identified during the development of the functional architecture [Buede, 2000: 215-216]. In addition, the physical architecture also describes the procedures by which the system is used [Buede, 2000: 218].

Physical architectures are either generic or instantiated. A generic physical architecture is developed in parallel with the functional architecture [Buede, 2000: 221] and partitions the resources into common categories without performance characteristics for the resources. The generic physical architecture also identifies procedures and controls affecting the system without specified attributes. An instantiated physical architecture is a generic physical architecture with performance characteristics or specified attributes of the system resources, procedures, and controls. This chapter presents the key phases and products within the physical architecture development.

B. GENERIC PHYSICAL ARCHITECTURE COMPONENTS

The first step of the physical architecture development is to identify the generic subsystems, components, and configuration items. A subsystem is a set of components which is less than the system itself. A component is a subset of physical resources of the system to which a subset of the system's functions have been allocated [after Buede, 2000: Glossary]. A configuration item is the lowest level of components. As an example of these levels of components, recall the two subsystem categories identified during the external systems diagram development - *people* and *communication and information systems*. One of the identified *people* subsystems was *staff*. Components of a commander's staff can be operations, logistics, and legal staffs. The configuration items, in this case, are the individuals which comprise the various levels of staffs. In fact, decomposing and reorganizing the two subsystem categories serves as an opportune starting point for describing the generic physical architecture.

1. People

The *people* subsystem category is comprised of three generic components, namely commanders (subordinate), staff, and personnel. All three types of the people components are subordinate to a commander, when one is designated. Recall that command is comprised of both the authority over subordinates and the responsibility for subordinates. Also recall that authority can be delegated. Differences between each of the three *people* components are primarily authority and responsibility.

a. Commanders (Subordinate)

When there is no specific entity designated responsible for the accomplishment of a mission, the commanders of the forces involved in the mission fall within the C2 system. When there is a specific entity designated responsible for the accomplishment of a mission, such senior commander falls outside the C2 system while subordinate commanders fall within the system. Subordinate commanders are responsible for and have authority over a portion of a senior commander's forces

b. Staff

As discussed previously, the staff subsystem can be comprised of several component staffs. Traditional staff divisions have been between administrative, intelligence, operations, logistics, plans, communications, and training [Mack, 1998: 172-176]. Given the purpose of the staff is to support the commander, staff organization is often tailored to meet the commander's needs or desires. In some cases commanders have joined traditionally separate component staffs just as operations and plans. These component staffs, in some cases, are further divided. In all cases, the configurable item for the staff is the individual person.

c. Personnel

Personnel are those persons who are assigned to a commander who are not subordinate commanders or staff. Specifically, personnel do not have authority over or responsibility for a portion of a commander's forces. A personal aide, a person standing watch, and a contractor are examples of personnel.

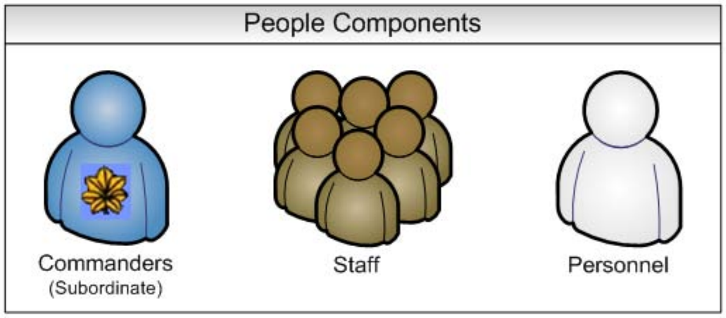

Figure 27. People Components

2. Communications and Information Systems

The second subsystem category, *communications and information systems*, consists of numerous generic components. Rice and Sammes [1989] present the basic components of a communications and information system. First, an information processing system requires an input component, an output component, a processor, and a memory component (sub-divided, potentially, into short-term and long-term storage) [Rice & Sammes, 1998: 37]. The information processing system is then connected by a communications system. The communications system can also connect other subsystems of the C2 system, namely people. In fact, the decomposition of a C2 system by Rice and Sammes is consistent with this thesis and doctrinal concepts presented in Chapter II. A C2 system, they state, "describes the combination of information systems (including communications systems), procedures and personnel used to effect the command and control process" [1989: 4]. Therefore, the major components of the communications and information subsystem are input interfaces, output interfaces, processors, memory/storage, and links.

a. Input Interface and Output Interface

The first two types of components of an information system are input and output interfaces. An interface is a resource for connecting two or more distinct systems or subsystems. The connection can be between the system, or subsystems, and external systems (external interface) or between subsystems (internal interface). When an interface is for accepting an input from an external system to the C2 system or subsystem, it is deemed an input interface. Conversely, when the function of the interface is for

disseminating an output to an external system from the C2 system or subsystem it is deemed an output interface. In the case of an internal interface, the interface can be designed to serve as both an input interface for one subsystem and an output interface of another subsystem. Input and output interfaces can be common electronic systems such as keyboards and video displays but can also be human actions such as spoken word.

b. Processor

The third type of component of an information system is processor. The purpose of the processor is either to transform information or convert data. First, through a combination of evaluation, synthesis, and analysis, a processor can transform data to information or information to data. Second, a processor can convert data from one format to another format. A human can serve as a processor for both transformation and data conversion, as well. Transforming information to or from knowledge, understanding, or wisdom requires a combination of functions, in particular processing and storing, and is therefore beyond the capabilities of a processor. Though a human can serve as a processor, when they transform information to or from knowledge, understanding, or wisdom they are not deemed a processor for purposes of this thesis. The distinctions between different forms of information is discussed in Appendix E: Functional Decomposition

c. Memory/Storage

Memory or storage is the fourth type of component of an information system. For the purpose of this thesis, memory is a component for storing information within the operating lifetime of the C2 system while storage is a component for storing information beyond the operating lifetime of the C2 system. As highlighted in the functional architecture, individual humans can be considered as memory and storage.

d. Link

Links are the final type of component for communication and information systems. A link connects the output interface of a subsystem with the input interface of another subsystem. The link can either be a physical connection via a designed system or

a remote connection. Remote connections allow the connected entities to be independently mobile while physical connections require the connected entities to move with each other.

As alluded to in the functional architecture, links can also be described by the method in which the information is transported. The information can be stored in physical matter such as a compact disk or human and transported between two geographically separate nodes. Additionally, the information can be transmitted through a medium, whether through a physical connection such as a waveguide or a remote connection such as acoustic waves. Links can differ in geographical size from a fraction of an inch on a circuit board to thousands of miles in the case of satellite communications.

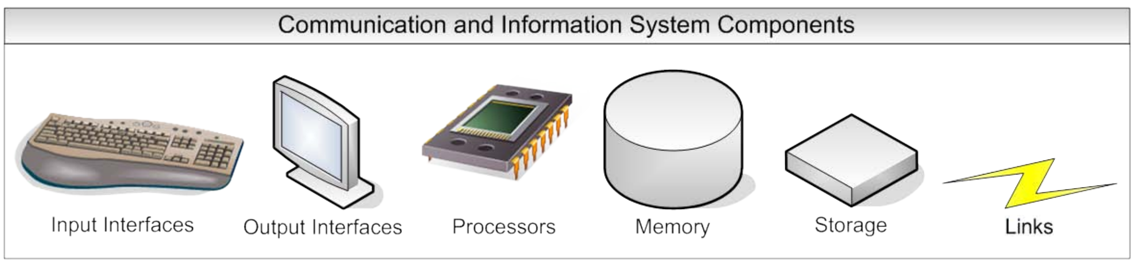

Figure 28. Communication and Information System Components

C. PHYSICAL ARCHITECTURE PROCEDURES AND CONTROLS

In addition to describing the physical resources which comprise the system, the physical architecture also describes the procedures by which the system is used [Buede, 2000: 218]. Similar to the physical components, procedures and controls also have attributes which affect the performance of the system and can have multiple instantiations. During the development of the physical architecture, at least six procedures and controls of the C2 system were identified with multiple instantiations. These generic procedures and controls include ethics, rules of engagement, weapons control status, and tactics, techniques, and procedures (TTPs) for C2.

Ethics are a set of moral principles or a system of moral values [Misch, 1994: 398]. For the purpose of this thesis, ethics are the basis by which the morality of an option or decision is judged. Rules of engagement are procedures and controls which

specify how and to what limit forces will initiate or continue combat engagement with other forces. Weapons control status denotes how and on which classification of targets weapons systems can be used. For purposes of this thesis, C2 TTPs were decomposed into three primary categories – situational awareness, decision authority, and allocation authority. Situational awareness is a category to group TTPs and controls that affect the sharing and dissemination of situational information within the networked force. Decision authority is a category to group TTPs and controls that affect the decisions within the networked force, which are applicable to the changing circumstances of the situation. Allocation authority is a category to group applicable TTPs and controls that affect the allocation of roles and responsibilities of the networked force.

D. INSTANTIATED PHYSICAL ARCHITECTURE

Once the generic components, procedures, and controls of the physical architecture were identified, the next step was to specify attributes and performance characteristics for each, from which alternative instantiated physical architectures could be designed and selected. There are many techniques for generating numerous physical architecture alternatives. The morphological box technique, suggested by Buede [2000: 222-226], was used for developing the physical architecture alternatives. "In the two-dimensional version a table is created with columns (or sometimes the rows) pertaining to the generic components of the physical architecture. Then the elements of each column are filled with competing specific instantiations of each component" [Buede, 2000: 223].

As in the functional architecture, there are varying levels within the morphological box. From the top-level morphological box to lower level boxes, the systems engineer describes alternative physical components with greater and greater detail. Taking the wrist watch example of a system, a generic component of the system would be a time presenter. The highest level of the morphological box for such component could list visual display and audio presentation as two alternatives. The next lower level for visual display could list analog display, digital display, and combination display. The next lower level for digital display could list 12-hour notation and 24-hour notation. This decomposition can be continued as is pertinent to the system under design.

The following sections present the top-level morphological boxes developed and discuss the instantiations of the components, procedures, and controls.

1. Physical Architecture Components

The top level morphological box for the physical components is presented in Table 9. This is by no means an exhaustive list of alternatives. Rather, this box served as a tool by which alternative physical architectures could be generated. The first row presents the generic components with the remaining entries in each column denoting the specific instantiations. Details concerning each of the alternatives for the generic physical components of the physical architecture are presented in the discussions below.

Commanders (Subordinate)	Staff	Personnel	Input Interface	Output Interface	Processor	Memory/ Storage	Links
Functional	Functional	Functional	Electromagnetic	Electromagnetic	Human	Human	Physical Matter - Connected
Geographic	Project/ Cross-Functional	Status	Voice	Voice	Mechanical Analog	Mechanical	Acoustic - Connected
Resource	Matrix		Acoustic Sound	Acoustic Sound	Electromechanical Analog	Electromechanical	Electromagnetic - Connected
Functional-Resource			Electromechanical	Electromechanical	Electromechanical Digital	Electromagnetic	Physical Matter - Remote
Functional- Geographic			Mechanical	Mechanical	Electronic Digital		Acoustic - Remote
			Scent	Scent			Electromagnetic - Remote
			Taste	Taste			

Table 9. Physical Components Morphological Box

a. Commanders (Subordinate)

Subordinate commanders are responsible for and have authority over a portion of a force. Commanders, whether subordinate or not, can be delineated in at least three possible ways. First, commanders' responsibilities can be divided functionally. For example, one commander can be responsible for airspace, while another is responsible for the subsurface of the ocean, while another is responsible for amphibious operations. Second, commanders' responsibilities can be divided geographically, that is each commander is responsible for everything which occurs within a geographic region. Third, commanders' responsibilities can be divided by the resources which they command. For example, in a joint operation a commander can be responsible for all of the service component forces, or in a multi-national operation a commander can be responsible for all of his or hers nation's forces, despite the functional capability or geographic location of the forces. Fourth and fifth, commanders' responsibilities can be divided through a combination of functional and resource or functional and geographic.

b. Staff

Staff may have authority over a portion of a senior commander's forces but do not have responsibility for such portion of forces. Staffs can be organized according to at least three major methods. First, a staff can be organized functionally. In this method staffs are organized according to services which they provide, such as intelligence, logistics, and personnel. This is a traditionally accepted method for staff organization, having been used extensively by the Prussian military [Hurley, 2005: 91-96]. Second, a staff can be organized by project or mission, or cross-functionally as Hurley [2005: 91-96] describes. In this method, the staff is organized into separate autonomous units, each for a particular task or mission [Forsberg, Mooz, & Cotterman, 2005: 171]. Each unit would be comprised of members with expertise in the different functional areas required for the project or mission. The members of the project/mission staff would report only to the project/mission leader and once the project/mission was accomplished, the staff would be disbanded. Third, a staff can be organized according to a matrix method, in other words a combination of functional and project/mission. In this

method there are leaders or managers defined for both projects/missions and functions. Staff personnel are assigned to leaders from both categories. The project/mission leader defines what the staff personnel should do while the functional leader defines how the staff personnel should executed their work [Forsberg, Mooz, & Cotterman, 2005: 173].

c. Personnel

Personnel are persons who do not have authority over or responsibility for a portion of a senior commander's forces. Personnel can be delineated in at least two ways. First, personnel can be divided by the functions they perform. Second, personnel can be divided by their status (e.g., Navy, Military, DoD Civilian, Contractor, Active Duty, Reserve, National Guard).

d. Input Interface

An input interface is a resource which connects an external system with the C2 system. As discussed in Appendix E: Functional Decomposition, communication of information is based on the exchange of data through observation. A C2 system input interface, therefore, transforms inputs, which are in the form of data, into useful information. C2 system input interfaces can therefore organized by the medium in which the data is received. Examples of medium divisions are electromagnetic, voice, acoustic sound, electromechanical, mechanical, scent, and taste.

e. Output Interface

A C2 system output interface transforms internal information into the form of data which then can be transported or transmitted to a subsystem or an external system. Therefore, C2 system output interfaces can be organized by the medium in which the data is transported or transmitted. Similar to input interfaces, examples of medium divisions are electromagnetic, voice, acoustic sound, electromechanical, mechanical, scent, and taste.

f. Processor

The purpose of the processor is either to transform information or convert data. Example instantiations of processors include human, mechanical analog, electromechanical analog, electromechanical digital, and electronic digital.

g. Memory/Storage

Memory is a component for storing information within the operating lifetime of the C2 system while storage is a component for storing information beyond the operating lifetime of the C2 system. Example instantiations of memory and storage include human, mechanical, electromechanical, and electromagnetic.

h. Link

Links connect the output interface of a subsystem with the input interface of another subsystem. As discussed in the body of the thesis, instantiations of links can be described by the type of connection (i.e., physical or remote) and by the medium in which the information is imbedded (e.g., physical matter, acoustic, electromagnetic).

2. Physical Architecture Procedures and Controls

As with the generic physical components, the morphological box technique was used to generate and describe the multiple instantiations of a few of the applicable procedures and controls. The top-level morphological box for procedures and controls is presented in Table 10. The first column presents the generic procedures and controls with the remaining entries in each row denoting the specific instantiations. Details concerning each of the alternatives for each of the procedures and controls of the physical architecture are presented in the discussions below.

Ethics	Absolute	Relativistic	Absolute-Relativistic	
Rules of Engagement	Command by Negation	Positive Command		
Weapons Control Status	Free	Tight	Hold	
C2 TTP: Situational Awareness	Centralized	Decentralized	Distributed	Isolated
C2 TTP: Decision Authority	Centralized	Decentralized	Distributed	Anarchic
C2 TTP: Allocation Authority	Centralized	Decentralized	Distributed	Anarchic

Table 10. Procedures and Controls Morphological Box

a. Ethics

Ethics are a set of moral principles or a system of moral values [Misch, 1994: 398]. For the purpose of this thesis, ethics are the basis by which the morality of an option or decision is judged. In particular, ethics are used as a procedure for or as a control on the function *Judge Response Options*. As will be shown in the development of the operational architecture, the resource assigned *Judge Response Options* is human. In essence, this thesis took the approach that a human is always within the command and control process. It is, therefore, the ethics and morals of such human that is a procedure for and control on the C2 system.

There are at least three general approaches to ethics, as described by Ackoff [1989: 6]. First, there is the absolute approach in which the judgment of morality is determined by compliance to a rule. Unfortunately, as Ackoff [1989: 6] states, "No set of ethical-moral rules has yet been formulated which does not lead to unresolvable problems." Second, there is the relativistic approach in which the judgment of morality is

determined by the situation and entities involved. This approach also raises difficulties when “what is ‘good’ for one person is ‘bad’ for another” [Ackoff, 1989: 8] that is involved. The final approach to ethics is a combination of both of the previous approaches.

b. Rules of Engagement

Rules of engagement (ROE) are procedures and controls which specify how and to what limit forces will initiate or continue combat engagement with other forces. The two instantiations of rules of engagement are command by negation and positive command. Command by negation accounts for those instances where the ROE allow actions to be taken “at the discretion of different levels of command unless negated by countermanding orders by higher command or by political authorities” [George, 1984: 227]. Positive command accounts for those instances where the ROE allow actions to “taken by military units only if expressly authorized by higher command or by political authorities at some point in the development of the crisis” [George, 1984: 227].

c. Weapons Control Status

Weapons control status is another control of a C2 system. It denotes how and on which classification of targets weapons systems can be used. Three instantiations of weapons control status are Free, Tight, and Hold [after NATO Standardization Agency, 2008: 2-W-2]. Free denotes that weapons systems may be fired at any target not positively recognized as friendly. Tight denotes that weapons systems may be fired only at targets recognized as hostile. Hold denotes that weapons systems may be fired only in self-defense or by formal order from higher authority.

d. Command and Control Tactics, Techniques, and Procedures

Tactics, techniques, and procedures (TTPs) for C2, though a bit more descriptive than the concept of C2 doctrine, is still a broad topic. For purposes of this thesis, C2 TTPs were decomposed into three primary categories each of which were comprised of four conceptual instantiations. The three primary categories were situational awareness, decision authority, and allocation authority. The first three

conceptual instantiations of each follow Baran's [1964] description of centralized, decentralized, and distributed networks, which is presented visually in Figure 29. Baran did not describe the fourth instantiation of the categories since he was attempting to describe a connected network for communications. The final conceptual instantiation for situational awareness equates roughly to solitariness while the final instantiation for decision authority and allocation authority is anarchic.

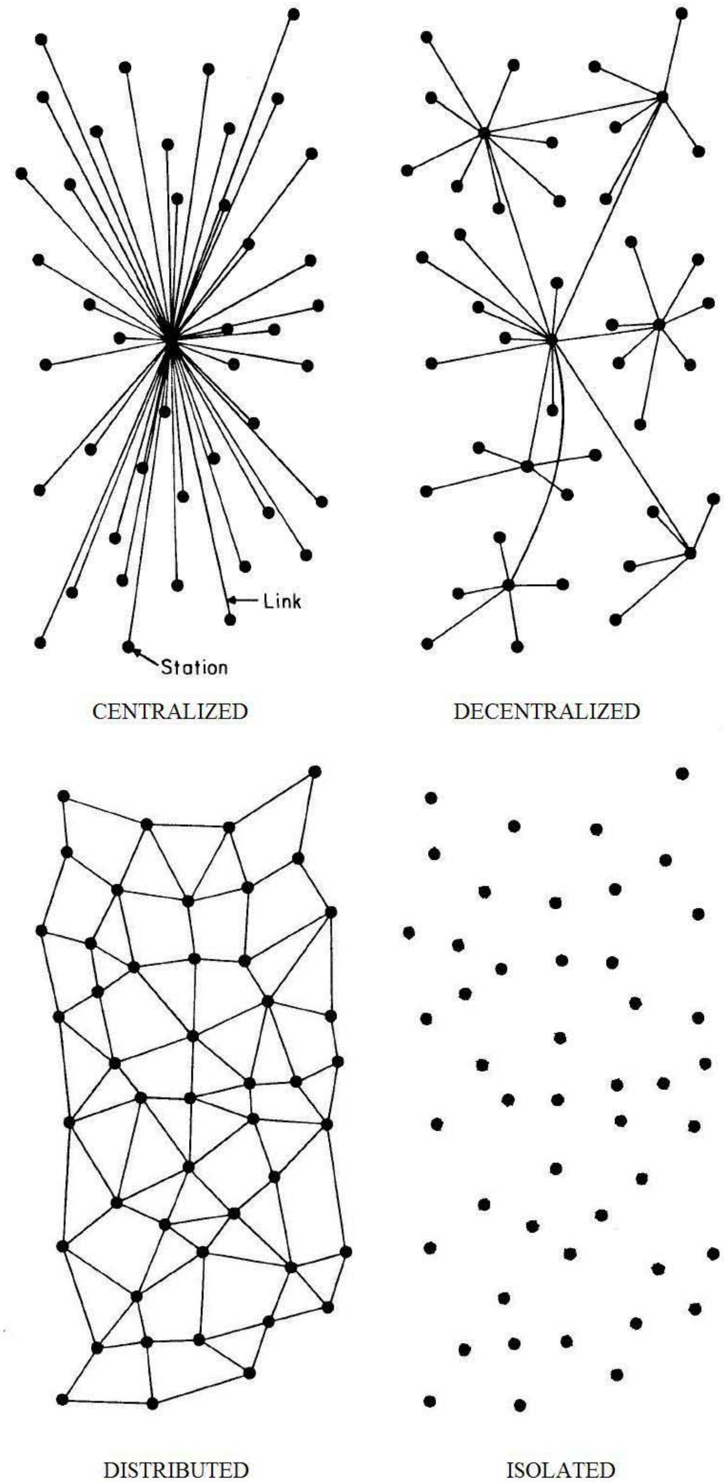

Figure 29. Centralized, Decentralized, Distributed, and Isolated
[after Baran, 1964: 2]

e. Situational Awareness

Situational awareness is a category to group TTPs and controls which affect the sharing and dissemination of situational information within the networked force. Centralized situational awareness describes the instances where a single entity or a single system collects and disseminates information pertaining to the situation. Decentralized situational awareness describes those instances where the sharing of situational information is divided into multiple levels with single line of communication. In other words, an entity or system at one level shares situational information with a portion of entities or systems at a lower level and with one entity or system at a higher level. Centralized situational awareness is divided into only two levels with the central entity or system comprising the highest level which shares information with all lower level entities or systems.

Distributed situational awareness describes those instances where situational information from one entity or systems is shared with two or more entities or systems, for every entity or system in the networked force. Finally, isolated situational awareness describes those instances where situational information is not shared between any entities or systems.

f. Decision Authority

Decision authority is a category to group TTPs and controls that affect the decisions within the networked force, which are applicable to the changing circumstances of the situation. Centralized decision authority describes the instances where a single entity or a single system is authorized to make decisions for the networked force. Decentralized decision authority describes those instances where the authority to make decisions concerning a portion of the network force follows a line of direct superiors. That is, decision authority is divided into levels where an entity at one level has authority over a portion of the entities at a lower level but in turn receives such authority by one entity at a higher level. Distributed decision authority describes those instances where the authority to make decisions follows multiple lines of superiors. In other words, decision authority over an entity resides in two or more entities which have a direct

connection with such entity. Anarchy is the absence of any authority [Mish, 1994: 42]. Therefore, anarchic decision authority describes those instances where the decision authority resides only in the entity itself, for all entities in the force.

The use of a distributed communications system to transport a decision and distributed decision authority are not equivalent. When a junior relies upon the decision of one superior, even if the decision can be communicated via many different means and methods, decision authority is not distributed. Decision authority in such case would be decentralized or centralized, but not distributed. The same holds for allocation authority.

g. Allocation Authority

Allocating authority is a category to group applicable TTPs and controls which affect the allocation of roles and responsibilities of the networked force. Centralized allocation authority describes the instances where a single entity or a single system is authorized to allocate roles and responsibilities to the networked force. Decentralized allocation authority describes those instance where the authority to allocate roles and responsibilities is divided into levels where an entity at one level has authority over a portion of the entities at a lower level but in turn receives such authority by one entity at a higher level. Distributed allocation authority describes those instances where the authority to allocate roles and responsibilities to an entity resides in two or more entities which have a direct connection with such entity. Anarchic allocation authority describes those instances where the authority to allocate a role or responsibility to an entity resides only in the entity itself, for all entities in the force.

E. ALTERNATIVE PHYSICAL ARCHITECTURES

Once instantiations for the generic components, procedures, and controls are identified the next step was to generate multiple physical architectures from which one or more could be selected to serve as an input to the operational architecture. Recall that a goal of this thesis was to better understand the influence of doctrine on the overall architecture of the material system in order to ensure developing net-centric systems and

net-centric doctrine meet the command and control needs of tactical naval forces. For this thesis, two alternative physical architectures were developed with varying instantiations of doctrine. When possible, all other components (i.e., communications and information systems), procedures, and controls were kept the same between the alternative architectures to highlight the impact of doctrine. Discussions of the two alternative architectures are presented in the following sections.

1. Alternative Physical Architecture #1

As presented previously, the focus of this thesis has been on those actions a future (i.e., ten to fifteen years from present) Surface Action Group would conduct to secure local sea control in traditional operating environments. Currently, U.S. tactical naval forces operate under Composite Warfare Commander (CWC) doctrine [Jane's Information Group, 2008]. Use of CWC doctrine dictates several of the physical architecture instantiations. First, the OTC's subordinate commanders are organized using a functional-resource combination. This is seen in the division of Principle and Functional Warfare Commanders and Coordinators. The Warfare Commanders (both Principle and Functional) can be delegated decision authority to respond with assigned assets. Coordinators are delegated allocation authority. Therefore, both decision authority and allocation authority are decentralized. The Composite Warfare Commander structure is presented in Figure 30.

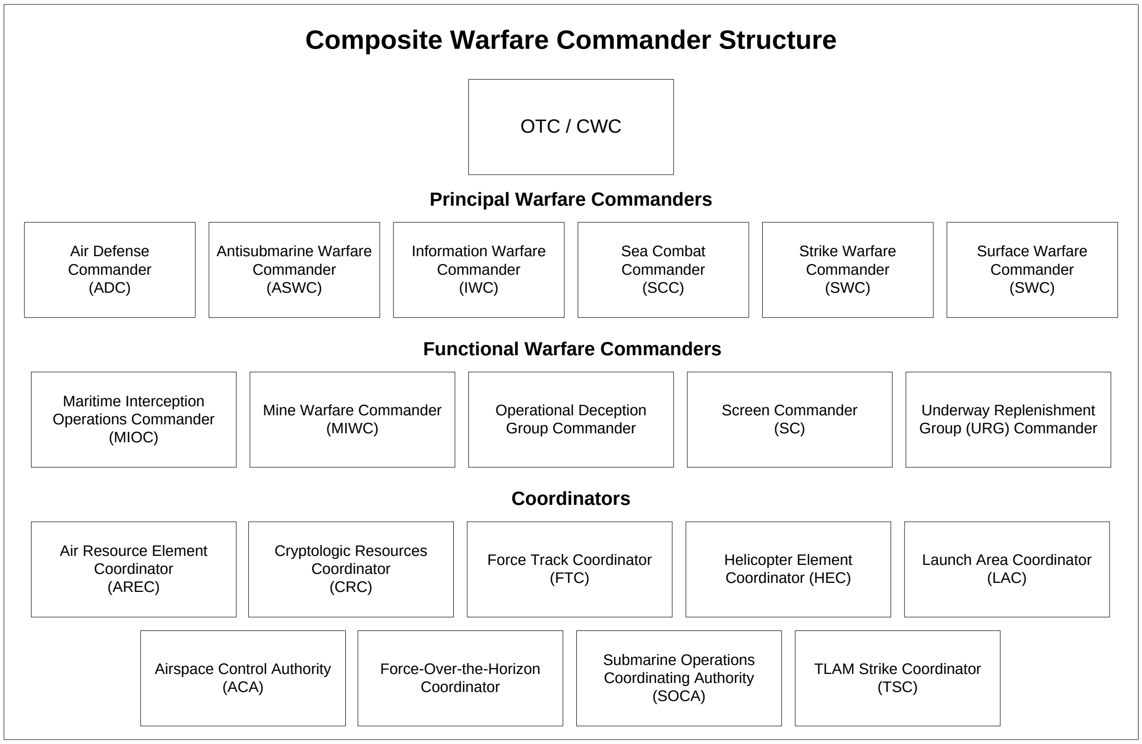

Figure 30. Composite Warfare Commander Structure
[from Jane's Information Group, 2008]

For the first physical architecture, CWC doctrine as currently written is used. Instantiations of commanders, decision authority, and allocation authority follow accordingly. In addition, the concept of Cooperative Engagement Capability (CEC), discussed in Chapter II, was assumed to have been designed and implemented not only for air defense but for surface and undersea warfare as well. The concept of CEC, as discussed in *The Cooperative Engagement Capability* [1995], with such expansion would dictate distributed situational awareness. Other physical architecture instantiations include the functional organization traditionally used for staff and personnel, absolute approach to ethics, adoption of command by negation, and a weapons control status of tight. Key physical architecture instantiations described above for the first physical architecture are highlighted with bold, italic font in Table 11.

Commanders (Subordinate)	Functional	Geographic	Resource	**Functional-Resource**	Functional-Geographic
Staff	***Functional***	Project/Task	Cross-functional/ Matrix		
Personnel	***Functional***	Status			
Ethics	***Absolute***	Relativistic	Absolute-Relativistic		
Rules of Engagement	***Command by Negation***	Positive Command			
Weapons Control Status	Free	***Tight***	Hold		
C2 TTP: Situational Awareness	Centralized	Decentralized	***Distributed***	Isolated	
C2 TTP: Decision Authority	Centralized	***Decentralized***	Distributed	Anarchic	
C2 TTP: Allocation Authority	Centralized	***Decentralized***	Distributed	Anarchic	

Table 11. Alternative Physical Architecture #1

2. Alternative Physical Architecture #2

For the second physical architecture the use of CWC doctrine as currently written is not used. The replacement "doctrine" under consideration for this thesis dictates subordinate commanders to be organized functionally and decision and allocation authority to be distributed. An expanded concept of CEC is still assumed, making situational awareness distributed. The remaining physical architecture instantiations remain consistent with the first alternative physical architecture (selection of functional

organization traditionally used for staff and personnel, absolute approach to ethics, the adoption of command by negation, and a weapons control status of tight).

Distributed decision authority describes those instances where the authority to make decisions follows multiple lines of superiors. Distributed allocation authority describes those instances where the authority to allocate roles and responsibilities to an entity resides in two or more entities which have a direct connection with such entity. The key physical architecture instantiations described above for the second physical architecture are highlighted with bold, italic font in Table 12.

Commanders (Subordinate)	***Functional***	Geographic	Resource	Functional-Resource	Functional-Geographic
Staff	***Functional***	Project/Task	Cross-functional/ Matrix		
Personnel	***Functional***	Status			
Ethics	***Absolute***	Relativistic	Absolute-Relativistic		
Rules of Engagement	***Command by Negation***	Positive Command			
Weapons Control Status	Free	***Tight***	Hold		
C2 TTP: Situational Awareness	Centralized	Decentralized	***Distributed***	Isolated	
C2 TTP: Decision Authority	Centralized	Decentralized	***Distributed***	Anarchic	
C2 TTP: Allocation Authority	Centralized	Decentralized	***Distributed***	Anarchic	

Table 12. Alternative Physical Architecture #2

F. CHAPTER SUMMARY

The physical architecture describes the resources which comprise the system, the procedures by which the system is used, and the controls on the system. During the development of the physical architecture, which is done concurrently with the development of the functional architecture, generic physical components and generic procedures and controls are identified. A set of instantiations is developed for each component, procedure, and control from which alternative physical architectures are developed. Such alternative physical architectures and other products of the first three phases of the system architectural process provide inputs for the development of the operational architecture.

VII. OPERATIONAL ARCHITECTURE

A. INTRODUCTION

The operational architecture provides a description of the system design, incorporating the products of the operational concept, functional architecture, and physical architecture. Major phases of the operational architecture development for this thesis were to allocate functions and requirements to the physical components and to describe the activation and control of functions. Analysis of the designs and full documentation of the architectures are subsequent phases of the operational architecture which were omitted due to the scope of this thesis. The feasibility of an analysis of designs using the architectural framework developed, however, was demonstrated using modeling and simulation.

B. GENERIC PHYSICAL COMPONENT FUNCTIONAL ALLOCATION

The first step in the development of the operational architecture is the allocation of functions from the functional architecture to components from the physical architecture. The initial phases of this process are conducted in conjunction with the co-development of the functional hierarchy and the generic physical architecture. These allocations are represented in Figure 51. through Figure 63. in Appendix F: Input-Output Relationships.

C. FUNCTIONAL FLOW, ACTIVATION, AND CONTROL

The second step in the development of the operational architecture is to define and analyze functional activation and control structures. Recall that the focus of this thesis has been on those actions a future (i.e., ten to fifteen years from present) Surface Action Group would conduct to secure local sea control in traditional operating environments. As delineated in the operational concept, one task a SAG securing local sea control must be capable of executing is contact prosecution. Modeling the functional flow, activation, and control of contact prosecution is necessary in the development of the operational architecture. Modeling the remaining sub-tasks and tasks, as well as the other

missions and their respective tasks and sub-tasks, would be required for the operational architecture development. Given the scope of this thesis and the magnitude of effort required to model all missions, tasks, and sub-tasks of a C2 system, the sub-task of contact prosecution was modeled to serve as an example for future development of the operational architecture.

The contact prosecution process was detailed for both of the alternative physical architectures developed. The contact prosecution functional flow for both physical architectures was the same and is presented in Figure 31. and continued in Figure 32. The remaining collection of contact prosecution process diagrams are presented in Appendix G: Operational Architecture.

The CP0 diagrams present the interactions of the system's top level functions from the functional architecture, the selected mechanisms from the physical architecture, and the procedures and controls identified in the physical architecture. First, starting in Figure 31. , the C2 system accepts inputs from external sensor systems, weapon systems, platforms, and people (e.g., established intent). The C2 system then processes the inputs, transports the resulting information, and reprocesses the information for presentation and response option generation. The current and past circumstances, as well as established intent when available, serve as inputs for generating a response option. The response option is then processed, transported, and reprocessed for selection, which begins in Figure 32.

If the response option is selected it becomes a response which is then processed, transported, and processed again. From the response an executable response is created which is processed, transported, and reprocessed to finally produce an assignment and/or warning to external systems and people; the flow through the figures is complete. If the response option was not selected, it would be processed, transported, and reprocessed to serve as input to generate a new response option, as shown at the bottom-left of Figure 31.

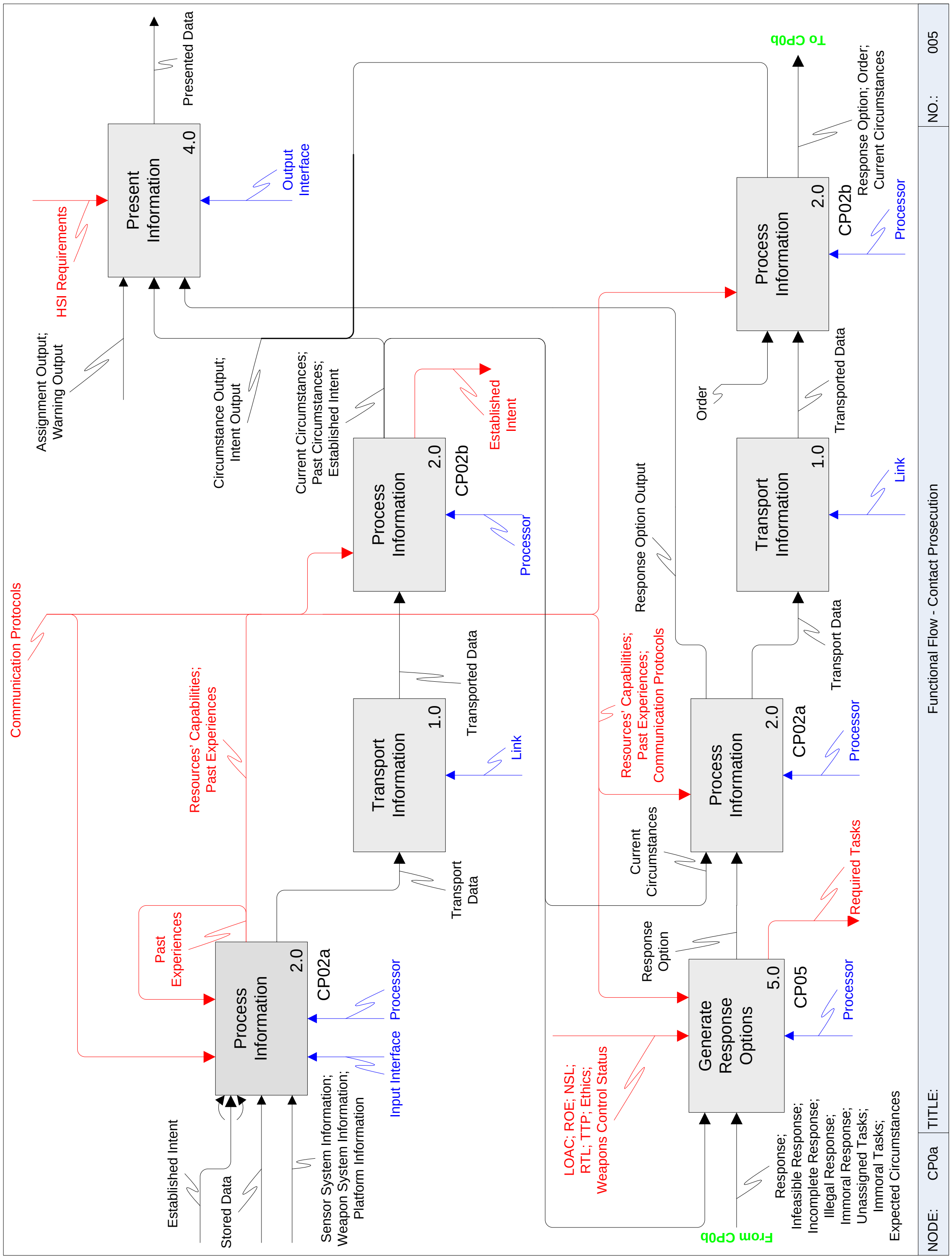

Figure 31. Contact Prosecution (CP0a)

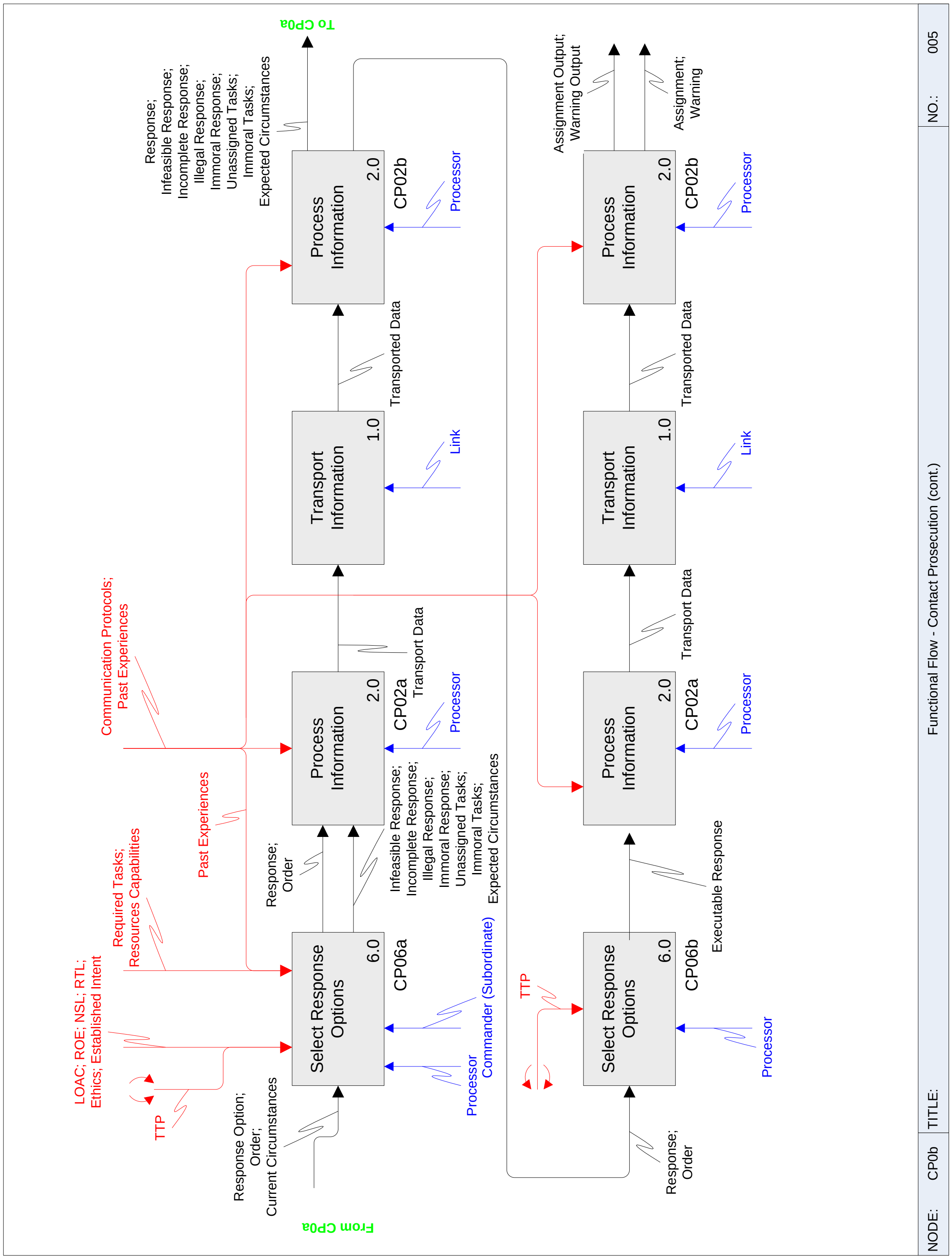

Figure 32. Contact Prosecution - Continued (CP0b)

Further detail of the functional activation and control for the top-level functions in the contact prosecution process is presented below in Table 13. The table is organized by function, output, required inputs, and required controls. Functions with multiple outputs are described with multiple lines in the output column. Outputs that can be generated by different, independent inputs are described with multiple lines in the input column. Outputs that require two or more inputs are described by listing all the required inputs in one line in the input column. For example, the Response Option output from *Generate Response Option* can be generated by multiple combinations of inputs. Response Option can be generated by the function with Current Circumstances, Past Circumstances, and Established Intent. Response Option can also be generated by the function with only Infeasible Response. Response Option can be generated by many other combinations of inputs, as well. Appendix G: Operational Architecture includes the complete table of the activation and controls, which includes sub-functions of the contact prosecution process.

Function	Output	Required Inputs	Required Controls
Transport Information	- Transported Data	- Transport Data	N/A
Process Information	- Transport Data	- Response Option	- Communication Protocols
		- Response	- Communication Protocols
		- Order	- Communication Protocols
		- Expected Circumstances	- Communication Protocols
		- Infeasible Response	- Communication Protocols
		- Incomplete Response	- Communication Protocols
		- Unassigned Tasks	- Communication Protocols
		- Illegal Response	- Communication Protocols
		- Immoral Response	- Communication Protocols
		- Immoral Tasks	- Communication Protocols
	- Past Experiences	- Stored Data	- Communication Protocols
	- Resources' Capabilities	- Stored Data	- Communication Protocols
	- Response Option Output	- Response Option	- Communication Protocols
		- Response Option Data	- Communication Protocols
	- Assignment	- Transported Data	- Communication Protocols
	- Warning	- Transported Data	- Communication Protocols
	- Assignment Output	- Transported Data	- Communication Protocols
	- Warning Output	- Transported Data	- Communication Protocols
	- Circumstance Output	- Transported Data	- Communication Protocols
	- Intent Output	- Transported Data	- Communication Protocols
	- Response	- Transported Data	- Past Experiences
	- Infeasible Response	- Transported Data	- Past Experiences
	- Incomplete Response	- Transported Data	- Past Experiences
	- Illegal Response	- Transported Data	- Past Experiences
	- Immoral Response	- Transported Data	- Past Experiences
	- Unassigned Tasks	- Transported Data	- Past Experiences
	- Immoral Tasks	- Transported Data	- Past Experiences

	- Expected Circumstances	- Transported Data	- Past Experiences
	- Response Option	- Transported Data	- Past Experiences
	- Order	- Order	- Past Experiences
	- Current Circumstances	- Transported Data	- Past Experiences
	- Past Circumstances	- Transported Data	- Past Experiences
	- Established Intent	- Transported Data	- Past Experiences
Store Information	- Stored Data	- Storage Data	N/A
Present Information	- Presented Data	- Assignment Output	- HSI Requirements
		- Warning Output	- HSI Requirements
		- Circumstance Output	- HSI Requirements
		- Intent Output	- HSI Requirements
		- Response Option Output	- HSI Requirements
Generate Response Options	- Response Option	- Current Circumstances - Past Circumstances - Established Intent	- Past Experiences - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List - Tactics, Techniques, and Procedures - Pre-planned Responses - Resources' Capabilities
		- Current Circumstances - Expected Circumstances - Established Intent - Response	- Past Experiences - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List - Tactics, Techniques, and Procedures - Pre-planned Responses - Resources' Capabilities
		- Established Intent - Infeasible Response	- Past Experiences - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List - Tactics, Techniques, and Procedures - Pre-planned Responses - Resources' Capabilities
		- Infeasible Response	- Past Experiences - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List - Tactics, Techniques, and Procedures - Pre-planned Responses - Resources' Capabilities

		- Established Intent - Incomplete Response - Unassigned Tasks	- Past Experiences - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List - Tactics, Techniques, and Procedures - Pre-planned Responses - Resources' Capabilities
		- Incomplete Response - Unassigned Tasks	- Past Experiences - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List - Tactics, Techniques, and Procedures - Pre-planned Responses - Resources' Capabilities
		- Illegal Response	- Past Experiences - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List - Tactics, Techniques, and Procedures - Pre-planned Responses - Resources' Capabilities
		- Established Intent - Immoral Response - Immoral Tasks	- Past Experiences - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List - Tactics, Techniques, and Procedures - Pre-planned Responses - Resources' Capabilities
		- Immoral Response - Immoral Tasks	- Past Experiences - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List - Tactics, Techniques, and Procedures - Pre-planned Responses - Resources' Capabilities

		- Current Circumstances - Past Circumstances - Established Intent	- Past Experiences - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List - Tactics, Techniques, and Procedures - Pre-planned Responses
		- Current Circumstances - Expected Circumstances - Established Intent	- Past Experiences - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List - Tactics, Techniques, and Procedures - Pre-planned Responses
		- Established Intent - Infeasible Response	- Past Experiences - Tactics, Techniques, and Procedures - Pre-planned Responses
	- Required Tasks	- Established Intent - Incomplete Response - Unassigned Tasks	- Past Experiences
		- Established Intent - Immoral Response - Immoral Tasks	- Past Experiences
		- Unassigned Tasks - Incomplete Response	- Past Experiences - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List - Tactics, Techniques, and Procedures - Pre-planned Responses - Resources' Capabilities
		- Illegal Response	- Past Experiences - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List - Tactics, Techniques, and Procedures - Pre-planned Responses - Resources' Capabilities

		- Immoral Response	- Past Experiences- Law of Armed Conflict- Rules of Engagement- Weapons Control Status- No Strike List- Restricted Target List- Tactics, Techniques, and Procedures- Pre-planned Responses- Resources' Capabilities
Select Response Options	Executable Response	- Response Option - Resources' Capabilities	- Past Experiences - Established Intent - Required Tasks - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List - Tactics, Techniques, and Procedures - Pre-planned Responses - Ethics
	Expected Circumstances	- Complete Response - Resources’ Capabilities - Current Circumstances	- Past Experiences - Required Tasks - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List

Table 13. Activation and Control of Top-level Functions

Since the contact prosecution functional flow for both physical architectures is the same, it is imperative for the systems engineer to describe the differences in the subsequent operational architectures through some means. Figure 33. presents a notional flow using the first alternative physical architecture while Figure 34. presents a notional flow using the second alternative physical architecture. Many of the details developed during the previous systems engineer process (e.g., inputs, outputs, controls, etc.) are omitted to emphasize the differences in operational architectures. The key changes in the notational flow from the first alternative to the second alternative are highlighted with yellow and bold boxes in Figure 34. The change from decentralized to distributed decision authority and from decentralized to distributed allocation authority is accounted for by including multiple entities which *Select Response Options* in parallel. The distributed situational awareness, in both architectures, is denoted by the multiple links in

Transport Information and their associated processors in *Process Information*. The significance of the exclamation points will be discussed in the following section.

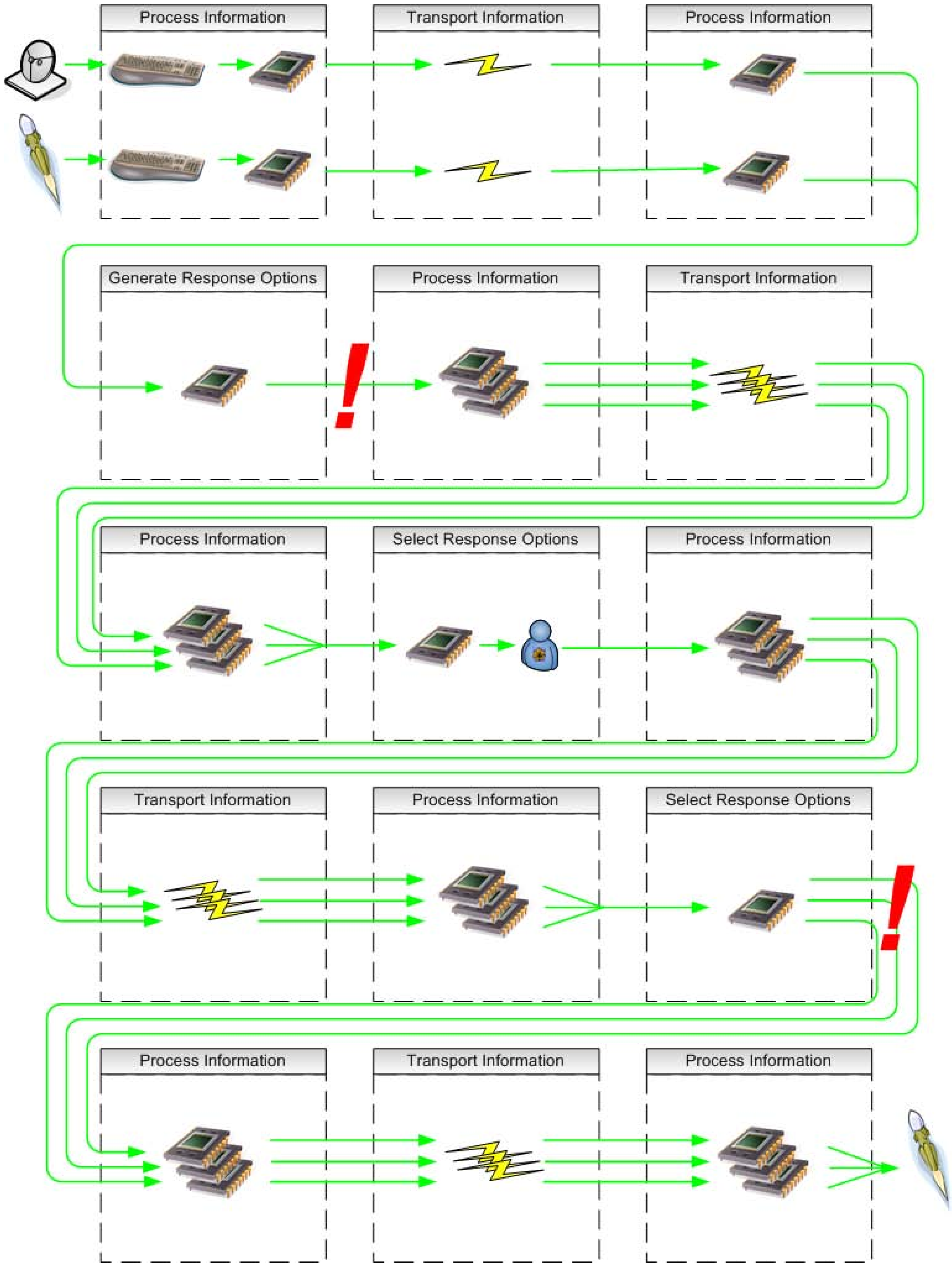

Figure 33. Notional Contact Prosecution Flow – Alternative #1

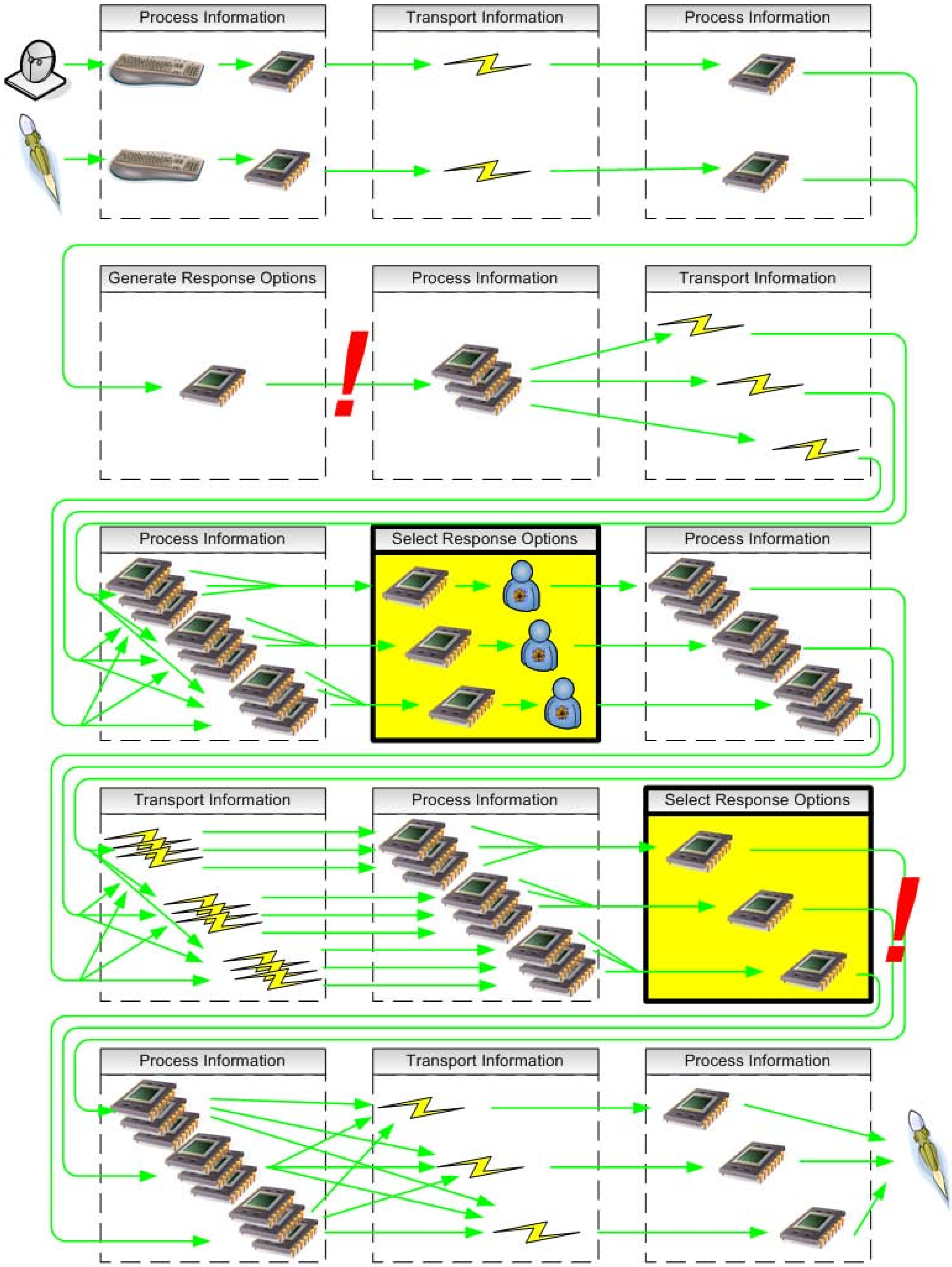

Figure 34. Notional Contact Prosecution Flow – Alternative #2

D. ANALYSIS OF DESIGNS

Analyses of the system designs include performance analyses and risk analyses. Performance analyses are conducted to discover "the range of performance that can be expected from a specific design or a set of designs that are quite similar" [Buede, 2000: 267] and to determine if a particular design or set of designs can achieve a related objective from the objectives hierarchy and its associated performance parameters. Risk analyses examine the ability of the design or set of designs to meet the desired level of performance in a diverse set of operational scenarios [Buede, 2000: 267]. In many cases, these analyses are conducted through modeling and simulation.

To demonstrate the feasibility of using the developed architectural framework to analyze and compare alternative designs, Arena®, version 10.0, was used. Arena® is a discrete-event modeling and simulation software developed by Rockwell Automation, Inc. A portion of the notional contact prosecution flow for both alternatives was modeled; the portion occurring between the red exclamation points as shown in Figure 33. and Figure 34. The top-level of the Arena® model is shown in Figure 35.

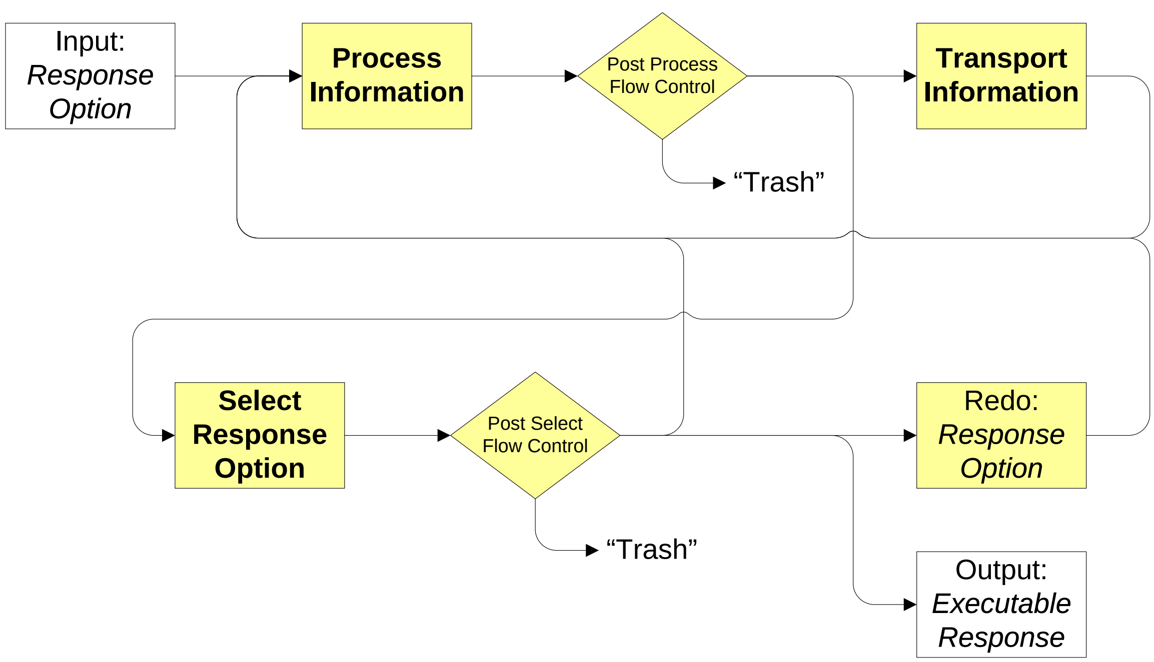

Figure 35. Top-level of Arena® Contact Prosecution Model

In both models, the first step is the creation of a response option. In the Alternative #1 model, three copies of the response option are created and transported using three different links. The first response option to be converted and processed for use is then used as input for the first time through *Select Response Options*. Once a response is selected, three copies are made and are then transported using three different links. The first response to be converted and processed for use is then used as an input for the second time through *Select Response Options*. Finally, an executable response is generated which marks the end of the Alternative #1 Arena® model.

In Alternative #2 model, nine copies of the response option are created and transported using nine different links; three links associated with each of three lines of mechanisms (e.g., subordinate commanders) to *Select Response Option*. The first response option to be converted and processed in each line is used as input to the first *Select Response Option* (i.e., *Evaluate Response Options* and *Judge Response Options*). The remaining response options are discarded. Once a response is selected by each line of entities, nine copies are made and are transported using nine different links; three links associated with each of three lines of mechanisms to *Select Response Option* a second time (i.e., *Assign Tasks to Resources*). Again, the first response to be converted and processed in each line is used while the remaining responses are discarded. Finally, an executable response is generated in each line of *Select Response Option*, which marks the end of the Alternative #2 Arena® model.

Response options were created with inter-arrival times following an exponential distribution. Characteristics and attributes of processes and resources were kept constant whenever possible. For example, the time for a subordinate commander to judge the morality of a response option followed the same distribution (i.e., a normal distribution with the same mean and variance) for all subordinate commanders in both models. Further details concerning characteristics and attributes of processes and resources, and further discussions of the simulation and results, is presented in Appendix G: Operational Architecture.

Performance of each alternative system designs should be unique and it is the objective of discrete-event modeling and simulation to identify those differences.

Differences in performance, as Buede [2000: 267] states, are almost always related to an objective in the systems objective hierarchy and its related performance parameters. Given that a significant difference between the two alternative system designs was the change from decentralized to distributed decision authority and allocation authority, differences in performance of the alternatives should be apparent in the *quality of response* (i.e., the fundamental objectives *quality of response decision* and *quality of allocations*).

In particular, a combination of three MoMs were selected to highlight differences in performance. First, the sum of MoP 5.2.2.2, time between response option being developed and response decision, and MoP 6.2.1, time between order of response execution by decision-authorized entity and completion of allocations by allocation-authorized entity, was recorded for each alternative design. Second, MoCE 5.5, consistency of response between decision-authorized entities, was also recorded. These MoMs were selected, in part, because of the ability of Arena® to capture the statistics.

Thirty replications were conducted for each alternative model. Each replication began with a warm-up time of three simulation-minutes to fill queues and task resources followed by ten simulation-minutes in which data was collected. For both alternative models approximately 100+ response options were created and served as input during the ten operational simulation-minutes. The minimum time from response option creation until the generation of an associated executable response, the sum of MoP 5.2.2.2 and MoP 6.2.1, was recorded for each response option and, in the case of Alternative #2, for each line of *Select Response Option* mechanisms. In addition, for Alternative #2, the executable responses for each response option were compared to determine consistency (i.e., MoCE 5.5). An overview of the simulation results is presented in Table 14.

	Alternative #1	**Alternative #2**
Sample Mean of Minimum Time (sec)	16.313	14.955
Sample Standard Deviation of Minimum Time	1.382	2.630
Mean percentage of grouped Executable Responses which are consistent	100%	86.6%

Table 14. Arena® Simulation Results - Overview

A box plot of the simulation results data is presented in Figure 36. Circles denote mild outliers and asterices denote extreme outliers. Further results of the simulations are presented in Appendix G: Operational Architecture.

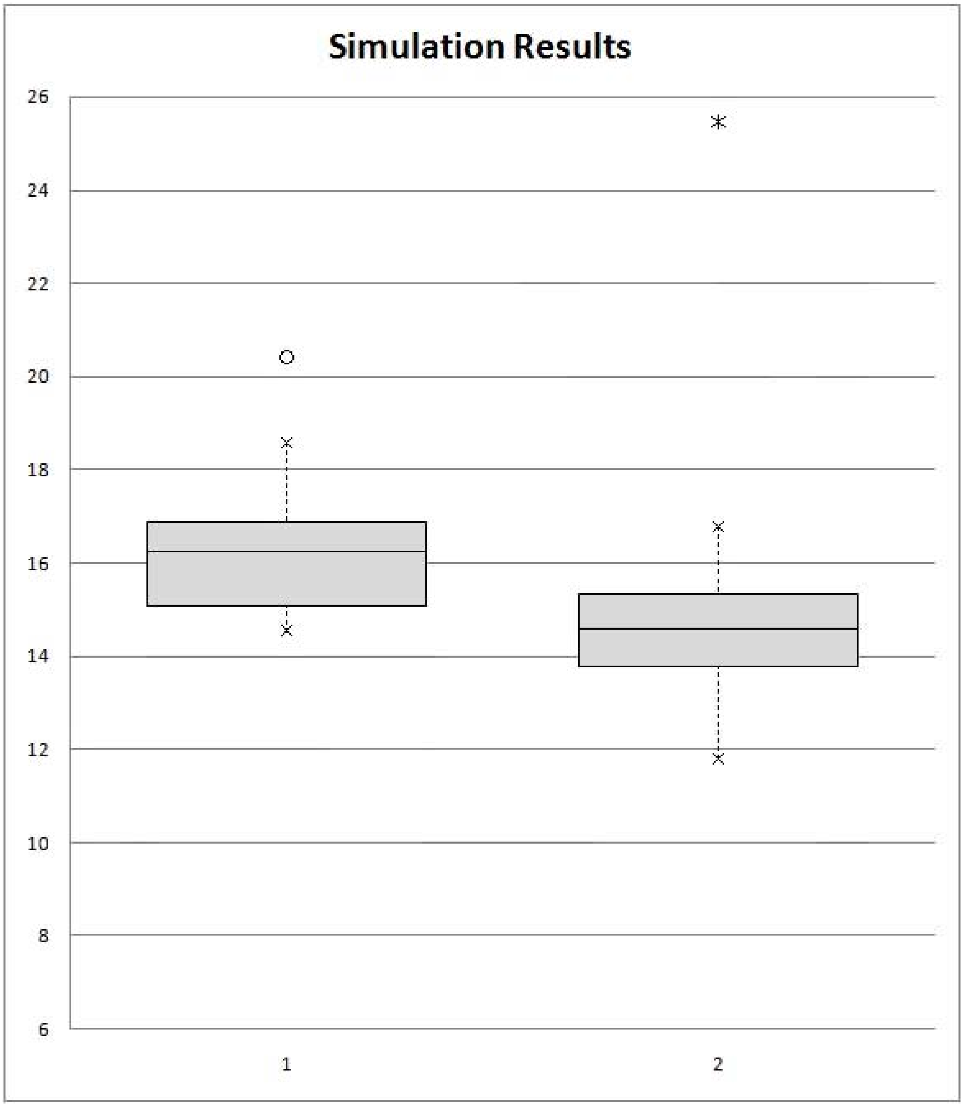

Figure 36. Arena® Simulation Results – Box Plot

Alternative #2 generates executable responses, on average, in less time than Alternative #1, but with more variance. In addition, Alternative #2 generates consistent executable responses approximately 87% of the time. Since Alternative #1 generates only one executable response for each response option, the consistency of response is 100% by default. Through hypothesis testing of the data collected, difference in the

mean minimum time was determined to be statistically significant. This demonstrates the possible performance differences between the two alternative designs.

The reader is warned not to draw specific conclusions on performance of the alternative system designs from the modeling and simulation results presented above. The objective of the modeling and simulation was not to conduct an analysis of design, but rather demonstrate the feasibility of using the developed architectural framework to conduct such analyses and compare alternative designs. Asserting performance superiority of one alternative over another should not be done for several reasons.

First and foremost, characteristics and attributes of the processes and resources were determined by the author and not by data collection or experimentation. For this reason statistically significant differences between designs apply only to the models developed and operationally significant differences cannot be assessed. Second, the modeling method used omitted many of the procedures and controls on the system identified in the architectural development. In other words, the models were a further abstraction of an already conceptual process.

Third, the Alternative #2 model developed was only one instance of the design solution space (i.e., the selection of three subordinated commanders and three processors in *Select Response Options*) possible from the operational architecture. Fourth, a value structure of value curves and weights for the systems objective hierarchy [Buede, 2000: Chapter 6], upon which trade-off decisions should be based, was not developed. Fifth, and finally, the above modeling and simulation represents only a few MoMs for only one sub-task out of numerous tasks and missions required of a Surface Action Group (SAG) to secure local sea control.

E. CHAPTER SUMMARY

The operational architecture presented provides a description of the system design by incorporating the products of the operational concept, functional architecture, and physical architecture. First, functions were allocated to the physical components. Second, the activation and control of the functions were described. Finally, the feasibility of an analysis of designs, using the architectural framework developed, was demonstrated

using modeling and simulation. Further research to complete the operational architecture and concerning the analysis of designs is discussed in Chapter VIII.

VIII. CONCLUSION

A. SUMMARY

This thesis dissected the complex engineering process of naval tactical command and control systems to identify the points of integration between doctrine and material. The goal was to better understand the influence of doctrine on the overall architecture of the material system to ensure developing net-centric systems and net-centric doctrine meet the command and control needs of tactical naval forces. To begin such study, this thesis presented concepts of command and control developed by military leaders and enthusiasts throughout history. Following this historical review, the thesis progressed through the system architectural methodology developed by Alexander Levis as presented by Buede [2000] and Levis and Wagenhals [2000].

The first phase in the architectural process was the development of the operational concept. The operational concept was a general vision of the system from the view of stakeholders [Buede, 2000]. It identified the boundaries of, inputs to, outputs from, objectives for, and requirements of the system. The second phase in the architectural process was the co-development of the functional architecture and the physical architecture.

The purpose of the functional architecture was to describe what the system was to do with the identified inputs to produce the desired outputs. The functional architecture described a hierarchy of the system's functions and detailed the relationships between the inputs and outputs of the system (i.e., described the sequence of functions converting an input into an output). The purpose of the physical architecture was to describe the resources that comprised the system, with resources for every function identified in the functional architecture [Buede, 2000: 215-216]. In addition, the physical architecture described the procedures by which the system was used [Buede, 2000: 218] and the controls on the system. Alternative, instantiated physical architectures were also developed as potential designs of the system. From such point the final phase of the architectural process, the development of the operational architecture, began.

The operational architecture provided a description of the system design by incorporating the products of the operational concept, functional architecture, and physical architecture. First, the functions developed in the functional architecture were allocated to the physical components developed in the physical architecture. Second, the activations and controls of the functions were described in a framework of the contact prosecution process, a use of a C2 system identified in the operational concept. The following sections of this chapter present key points and recommendations identified during the process of this thesis as well as potential areas for further research.

B. KEY POINTS AND RECOMMENDATIONS

During the process of this thesis, several key points were identified which are crucial for understanding the influence of doctrine on the overall architecture of a naval tactical command and control system. The first key point, identified in Chapter II, was that the overall process of command and control and the process internal to the C2 system are not the same. Rather, a C2 system is the means by which the C2 process is executed. This had implications at several points in the architectural process. First, it impacted the view of what was internal and what was external to the C2 system (described in the operational concept). The view of what was internal to the C2 system impacted the identified resources of the C2 system (detailed in the physical architecture). The view of what was external to the C2 system impacted the identified inputs and outputs and subsequently the functions of a C2 system (detailed in the functional architecture).

The second key point, following from the first, is that doctrine has significant impact on each phase of the system architectural process. In the operational concept, doctrine impacts which missions and tasks a naval force is expected to execute. It also impacts, as discussed above, the view of the system's boundaries. In the functional architecture, doctrine impacts what functions a C2 system must accomplish. In the physical architecture, doctrine impacts the resources, or mechanisms, available and how they are assigned to functions. Additionally, doctrine impacts controls on mechanisms and the types of resources which execute a function (e.g., only humans can determine morality of a response). Finally, in the operational architecture, doctrine impacts what

alternative physical architectures are considered for combination with the functional architecture (e.g., whether a single commander or multiple commanders have decision making and/or allocation authority).

The author recommends that systems engineers and analysts adopt the conceptual view that the commander is outside of the command and control system during design, development, and simulation. First, this view addresses the function-process-system view presented in historical and doctrinal publications; command is a function by which a responsible entity takes inputs (e.g., mission objective, assigned forces, operating environment, adversary's capabilities, etc.) to produce the desired output (i.e., accomplishment of the mission objective), command and control is the process by which the inputs generate the outputs, and a C2 system is the means by which the process is executed. Second, this view enables the use of a C2 system and the execution of the C2 process despite those situations when no specific entity is designated responsible for the accomplishment of a mission.

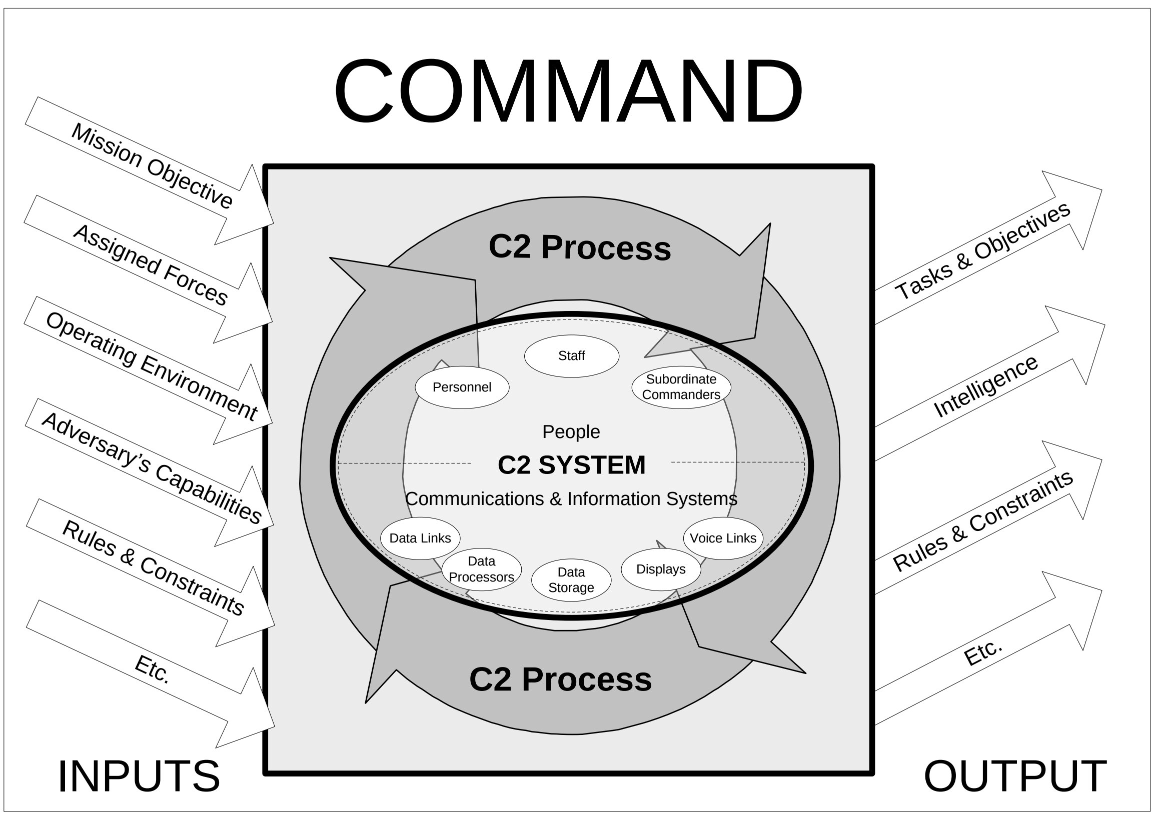

Figure 37. Command and Control: Function-Process-System

The author also recommends the use of the selected measures of merit, developed in the operational concept, for measuring the effectiveness of network-centric command and control systems. These measures of merit were an aggregation of measures and concepts presented in numerous publications and were selected due to their alignment with the network-centric refined problem statement:

> A responsive and robust command and control system which connects dispersed forces and enables such forces to self-synchronize and allocate resources to mass effects in order to meet the established intent at the tactical level of war.

These selected measures of merit are presented, again, in Table 15.

1.2.1	MoP	Number of sources confirming information
1.3.1	MoP	Time between changing circumstances and observation
1.3.2	MoP	Time between the observation and the completion of processing the data into information
1.3.4.4	MoP	Probability of shelf-life is less than time between updates
1.4.1.2	MoP	Percentage of nodes which are capable of viewing information
1.4.2.2	MoP	Percentage of nodes which are capable of acting on information
1.5.2.4	MoP	Percentage of Essential Elements of Information (EEI) met
1.5.2.5	MoP	Percentage of commander's Essential Elements of Friendly Information (EEFI) met
1.8.1.1	DP	Spatial resolution of observation capability
1.8.1.2	DP	Temporal resolution of observation capability
1.9.2	MoP	Number of nodes in the life of the information to which it can be attributed
1.9.1	MoP	Differential between time information is received by a node and when information can be attributed
2.1.1.2	MoP	Percentage of total decision-authorized entities that are available via existing relationships and connections
2.1.1.3	MoP	Percentage of total allocation-authorized entities that are available via existing relationships and connections
2.1.1.4	MoP	Percentage of total action-authorized entities that are available via existing relationships and connections
2.1.2.1.2	MoP	Time between operational failures for the network of connections
2.1.2.2.2	MoP	Probability of operational failure for network of connections
2.3.3.1.2	MoP	Quantity of overflow beyond capacity for the network of relationships and connections
2.4.1.1.4	MoP	Total geographical volume of relationships and connections
2.4.2.1.3	MoP	Median time required to reconfigure relationships and connections to meet changing circumstances and/or necessary responses
2.4.2.2	MoP	Number of possible solutions for required reconfiguration to meet changing circumstances and/or necessary responses
2.4.3.1.4	MoP	Median percentage of nodes which each relationship or connection is capable of connecting with
2.4.4.1.3	MoP	Number of nodes the network of connections are capable of adding
2.4.4.2.7	MoP	Median time required to add all relationships and connections to meet changing circumstances and/or necessary responses
2.4.5.1.3	MoP	Median geographical range nodes can maneuver while maintaining needed relationships or connections
3.2	MoP	Consistency of established intent between forces

4.2	MoP	Consistency of awareness between forces of rules and constraints which are applicable to such forces
5.1.2	MoP	Consistency of response with established intent
5.1.4	MoP	Consistency of response with rules and constraints
5.2.1	MoP	Time between receipt of information concerning changing circumstances and acknowledgement of receipt
5.2.2.1	MoP	Time between acknowledgement of receipt of information concerning changing circumstances and response option being developed
5.2.2.2	MoP	Time between response option being developed and response decision
5.2.3	MoP	Time between response decision and order of response execution by decision-authorized entity
5.3.2	MoP	Median number of connections between decision-authorized entity and action-authorized entity
5.3.4	MoP	Percentage of entities connected by existing relationships and connections which are authorized to make a specific decision concerning a specific change in circumstances
5.4.1	MoP	Number of distinct response solutions generated by decision-authorized entities concerning a specific change in circumstances
5.5.2	MoP	Percentage of action-authorized entities with conflicting orders from decision-authorized entities
6.1.3.3	MoP	Percentage of action-authorized entities which are allocated a role or responsibility which they cannot accomplish
6.2.1	MoP	Time between order of response execution by decision-authorized entity and completion of allocations by allocation-authorized entity
6.2.2	MoP	Time between allocation of role or responsibility and commencement of role or responsibility by action-authorized entity
6.3.2	MoP	Median number of connections between allocation-authorized entity and action-authorized entity
6.3.4	MoP	Percentage of entities connected by existing relationships and connections which are authorized to make allocations concerning a specific decision
6.4.2	MoP	Percentage of roles and responsibilities which are required for the specific decision which are not allocated

Table 15. Selected Measures of Merit

C. AREAS FOR FURTHER RESEARCH

The approach and results of the thesis demonstrated only a portion of the system engineering process (i.e., system architecture phases) focused on a small portion of the command and control problem (i.e., the needs of a Surface Action Group tasked to secure local sea control in traditional operating environments), all at a highly conceptual level. This thesis, its approach, and its conclusions provide future researchers with numerous areas of potential study.

First, given that the focus of this thesis was on the interaction of doctrine and material in the system architecture process, this thesis can serve as an example for further research on the implications of organization, training, leadership, personnel, and facilities on the system engineering process. Second, future researchers could expand the

presented architectural products to include other missions, tasks, forces, and scenarios. Third, future researchers may consider validating the proposed hierarchy of systems objectives. This can be done through a survey of potential stakeholders or through an analysis of alternatives.

Fourth, future researchers may consider identifying the best method to model the architecture framework presented in this thesis in order to simulate the alternative C2 systems. Though this thesis presented one method for modeling and simulating the system (i.e., discrete-event modeling and simulation using Arena®) it should not be accepted as the best method. Future researchers could conduct a trade-off study of methods and tools to model and then simulate the architectural framework developed. Fifth, future researches could develop additional alternative system architectures using the framework developed. Sixth, and finally, future researchers could analyze the two alternative architectures presented, or any additionally developed, using either the models presented or other models developed in the future.

D. FINAL SUMMARY

The systems engineer, among other things, must elicit the operational needs of the customer and develop a system architecture from which specialized engineers can design and build the applicable configurable items. Network-Centric Warfare (NCW) is an operational concept the U.S. military has identified to meet its operational needs which has major implications on the development of command and control systems. This thesis was conducted in part to provide a better understanding of the influence of doctrine on the overall architecture of command and control system. In addition, it was intended to assist in the development and integration of net-centric systems and net-centric doctrine to meet the command and control needs of future tactical naval forces.

APPENDIX A: SCENARIO DEVELOPMENT

The three settings and a collection of associated scenarios developed are presented below. Some scenarios, and portions of particular scenarios, are omitted due to dissemination limitations on information from references used in development.

ALPHA	Anti-submarine Warfare (ASW) + Surface Warfare (SUW)
Setting	The year is 2020. Country BROWN (a U.S. adversary) submarines are suspected to be operating in the vicinity of the STRAIT OF CONCERN, which lies between Country GREEN (a U.S. ally) and BROWN. A U.S. Navy Surface Action Group (SAG) is tasked with maintaining local sea control of the STRAIT OF CONCERN for the potential transit of high value units. While conducting anti-submarine operations in the strait, the SAG is confronted with a threatening swarm of small boats emanating from BROWN's national waters. The SAG must continue anti-submarine operations while addressing the swarm of small boats. The year is 2020. The SAG consists of 1 CG and 2 DDG.
Actors – Systems & Stakeholders	**Officer in Tactical Command (OTC)** Combatant Commander Submarine Swarm Boats Sensor System ASW Platform Common Tactical Picture (CTP) system Weapon System
Flow of events	1. Combatant Commander issues OPORD to OTC 2. OTC assigns sensor systems to search for undersea targets 3. OTC assigns sensor systems to search for surface targets 4. OTC assigns sensor systems to search for air targets 5. OTC assigns sensor systems to search for electronic warfare targets 6. CTP system alerts OTC of probable undersea target and location [a, b]. 7. OTC assigns additional sensor systems to probable undersea target for confirmation [a, b]. 8. CTP system provides confirmation of undersea target to OTC [a, b]. 9. OTC assigns sensor system(s) to continually track the confirmed undersea targets [a, b]. 10. OTC validates confirmed undersea target complies with guidance, LOAC, ROE, and other restrictions [a, b]. 11. OTC determines desired effect (DETERRENCE) against

	confirmed undersea target [a, b]. 12. Potential deterrence options are generated and are presented to OTC [a, b]. 13. OTC conducts risk assessment of deterrence options [a]. 14. OTC orders ASW platform to proceed to confirmed undersea target as a deterrence [a, b]. 15. OTC reviews status of the confirmed undersea target noted in CTP system [a, b]. 16. OTC assesses deterrence effectiveness of confirmed undersea target and determines whether to engage confirmed undersea target [a, b]. 17. CTP system alerts OTC of probable surface targets and location [a]. 18. OTC assigns additional sensor systems to probable surface targets for confirmation [a]. 19. CTP system provides confirmation of surface targets to OTC [a]. 20. OTC assigns sensor system(s) to continually track the confirmed surface targets[a]. 21. OTC validates confirmed surface targets comply with guidance, LOAC, ROE, and other restrictions [a]. 22. OTC determines desired effect(s) against confirmed surface targets [a]. 23. Potential engagement options are generated through weapon-target pairings (WTPs) and are presented to OTC [a]. 24. OTC conducts risk assessment of engagement options [a]. 25. OTC orders confirmed surface targets to be engaged with selected engagement option [a]. 26. OTC reviews status of the confirmed surface targets noted in CTP system [a]. 27. OTC assesses status of the confirmed surface targets and determines whether to re-engage [a].
Inputs	… Probable Target Detection Probable Target Location Target Confirmation Precise Location of Confirmed Target Confirmed Target Window of Vulnerability Refined Window of Vulnerability for Confirmed Target Engagement Options Deterrence Options
Outputs	Deterrence Order Engagement Order Re-engagement Order
References	a. JP 3-60: Joint Targeting (2007)

	b. Bindi, V.C., Baker, J., Billington, R., Gallassero, T., Gueary, J., Harts, et al. (1997).

Table 16. Scenario ALPHA – 1

BRAVO	Anti-submarine Warfare (ASW) + Air Defense (AD)
Setting	Country BROWN (a U.S. adversary) submarines are suspected to be operating in the vicinity of the STRAIT OF CONCERN, which lies between Country GREEN (a U.S. ally) and BROWN. A U.S. Navy Surface Action Group (SAG) is tasked with maintaining local sea control of the STRAIT OF CONCERN for the potential transit of high value units. While conducting anti-submarine operations in the strait, the SAG is confronted with several incoming cruise missiles emanating from BROWN's national air space. The SAG must continue anti-submarine operations while addressing the cruise missiles. The year is 2020. The SAG consists of 1 CG and 2 DDG.
Actors – Systems & Stakeholders	**Officer in Tactical Command (OTC)** Combatant Commander Submarine Cruise Missiles Sensor System ASW Platform Common Tactical Picture (CTP) system Weapon System
Flow of events	1. Combatant Commander issues OPORD to OTC 2. OTC assigns sensor systems to search for undersea targets 3. OTC assigns sensor systems to search for surface targets 4. OTC assigns sensor systems to search for air targets 5. OTC assigns sensor systems to search for electronic warfare targets 6. CTP system alerts OTC of probable undersea target and location [a, a]. 7. OTC assigns additional sensor systems to probable undersea target for confirmation [a, a]. 8. CTP system provides confirmation of undersea target to OTC [a, a]. 9. OTC assigns sensor system(s) to continually track the confirmed undersea targets [a, a]. 10. OTC validates confirmed undersea target complies with guidance, LOAC, ROE, and other restrictions [a, a]. 11. OTC determines desired effect(s) against confirmed undersea target [a, a]. 12. Potential deterrence options are generated and are presented to OTC [a, a]. 13. OTC conducts risk assessment of deterrence options [a, a].

	14. OTC orders ASW platform to proceed to confirmed undersea target as a deterrence [a, a]. 15. OTC reviews status of the confirmed undersea target noted in CTP system [a, a]. 16. OTC assesses deterrence effectiveness of confirmed undersea target and determines whether to engage confirmed undersea target [a, a]. 17. CTP system alerts OTC of probable air targets[a]. 18. OTC assigns additional sensor systems to probable air targets for confirmation [a]. 19. CTP system provides confirmation of air targets to OTC [a]. 20. OTC assigns sensor system(s) to continually track the confirmed air targets[a]. 21. OTC validates air targets comply with guidance, LOAC, ROE, and other restrictions [a]. 22. OTC determines desired effect(s) against the confirmed air targets [a]. 23. Potential engagement options are generated through weapon-target pairings (WTPs) and are presented to OTC [a]. 24. OTC conducts risk assessment of engagement options [a]. 25. OTC orders to engage confirmed air targets with selected engagement option [a]. 26. OTC reviews status of the air targets noted in CTP system [a]. 27. OTC assesses status of the air targets and determines whether to re-engage [a].
Inputs	… Probable Target Detection Probable Target Location Target Confirmation Precise Location of Confirmed Target Confirmed Target Window of Vulnerability Refined Window of Vulnerability for Confirmed Target Engagement Options Deterrence Options
Outputs	Deterrence Order Engagement Order Re-engagement Order
References	a. JP 3-60: Joint Targeting (2007) b. Bindi, V.C., Baker, J., Billington, R., Gallassero, T., Gueary, J., Harts, et al. (1997).

Table 17. Scenario BRAVO – 1

CHARLIE	Maritime Interception Operations (MIO) + Surface Warfare (SUW)
Setting	Country BLACK is suspected of harboring anti-U.S. terrorist. The anti-U.S. terrorists are suspected of attempting to smuggle weapons of mass destruction through the STRAIT OF CONCERN, which lies between country GREEN (a U.S. ally) and country BROWN (a U.S. ally), via commercial shipping carriers. A U.S. Navy Surface Action Group (SAG) is tasked with conducting maritime interception operations (MIO) in the vicinity of the STRAIT OF CONCERN in response to the threat. While conducting MIO of a target of interest, the SAG is confronted with a threatening swarm of small boats emanating from BROWN's national waters. The SAG must continue current MIO of the target of interest while addressing the swarm of small boats. The year is 2020. The SAG consists of 1 CG, 1 DDG, and 1 LCS.
Actors – Systems & Stakeholders	**Officer in Tactical Command (OTC)** … Suspect Vessel Support Forces Swarm Boats Sensor System Common Tactical Picture (CTP) system Weapon System
Flow of events	1. … 2. Sensor system reports probable surface targets and location to CTP system [a]. 3. OTC assigns additional sensor systems to probable surface targets for confirmation [a]. 4. Data from sensor system(s) is correlated and fused to determine probable surface targets precise location. Sensor System(s) report precise location of probable surface targets to CTP system [a]. 5. Sensor system(s) provide confirmation of surface targets – swarm boats – to CTP system [a]. 6. Sensor system(s) provide swarm boats' window of vulnerability to CTP system [a]. 7. OTC assigns sensor system(s) to continually track the swarm boats. 8. Sensor system(s) provide refined window of vulnerability of swarm boats to CTP system [a]. 9. OTC validates swarm boats comply with guidance, LOAC, ROE, and other restrictions [a]. 10. OTC determines desired effect(s) against swarm boats [a]. 11. Potential engagement options are generated through weapon-target pairings (WTPs) and are presented to OTC [a]. 12. OTC conducts risk assessment of engagement options [a].

	13. OTC orders swarm boats to be engaged with selected engagement option [a]. 14. Weapon system engages swarm boats [a]. 15. OTC reviews status of the swarm boats noted in Common Tactical Picture system [a]. 16. OTC assesses status of the swarm boats and determines whether to re-engage [a].
Inputs	… Rules of Engagement (ROE) Law of Armed Conflict (LOAC) Probable Target Detection Probable Target Location Target Confirmation Precise Location of Confirmed Target Confirmed Target Window of Vulnerability Refined Window of Vulnerability for Confirmed Target Engagement Options
Outputs	… Engagement Order Re-engagement Order
References	a. JP 3-60: Joint Targeting (2007)

Table 18. Scenario CHARLIE - 1

APPENDIX B: TARGET ENGAGEMENT

Several target engagement process models have been developed and presented in service documents. The detect-to-engage sequence for prosecuting threats, as described by Athans [1986] and Payne [2006], is a model used for the training of future officers in the U.S. Navy. Conversely, the Find-Fix-Track-Target-Engage-Assess (F2T2EA) process model has been used with respect to time-sensitive targeting [Committee on C4ISR for Future Naval Strike Groups, 2006: 42; Hunerwadel, 2006]. F2T2EA has been adopted by all services for dynamic and time-sensitive targeting [JP 3-60, 2007] at the operational level of war.

Though the detect-to-engage sequence, F2T2EA, and the general targeting process presented in JP 3-60 [2007] are all similar, differences in terminology can confound a reader. Therefore, the F2T2EA engagement process model and associated terminology as detailed in JP 3-60 [2007: Ch II], was selected by the author to serve as a foundation for the development of the tactical threat and target engagement scenarios. The steps of F2T2EA [JP 3-60, 2007] are explained in below and presented in Figure 38. and Figure 39.

FIND

Input: Inputs to the find step are clear priorities and guidance from the Joint Force Commander, intelligence of the battlespace to include areas of interest, and intelligence, surveillance, and reconnaissance (ISR) collection plans.

Phase: The intelligence collection process is the primary driver of the find step. Detections which meet predetermined criteria are deemed emerging targets. An emerging target's criticality, time-sensitivity, and probability of being a target is further refined in the find phase. Emerging targets which are considered potential targets are moved to subsequent steps. Those deemed not to be a potential target are dropped from the process. If it is not known whether a emerging target is a potential target or not, the detection remains in the find step.

Output: The output of the find step is potential targets "detected and nominated for further development" [JP 3-60, 2007: Ch II, 15].

FIX

Input: The inputs to the fix step include potential targets from the find step and sensor information on the target.

Phase: In the fix step, the identification of potential targets is confirmed and the target's precise location is determined through means of data correlation and fusion. Also during the fix step, the target's window of vulnerability is established for prosecution and prioritization.

Output: The output of the fix step is the identification, classification, and confirmation of the target, the location of the target accurate enough for target engagement, and the target window of vulnerability.

TRACK

Input: Inputs to the track step are a confirmed target with location accurate enough for target engagement.

Phase: In the track step, sensors are selected to continually track the confirmed target. The sensors are selected according to prosecution needs and prioritization based on all targets' window of vulnerability. The targets' window of vulnerability is further refined by the data collected from the assigned sensors.

Output: The output of the track step is a continuous track of the confirmed target, the sensor prioritization scheme, and updated target window of vulnerability.

TARGET

Input: The inputs for the target step include:

1. Identified, classified, located, and prioritized target
2. Collateral damage guidance
3. Rules of Engagement (ROE)

4. Law of Armed Conflict (LOAC)
5. No-strike List (NSL)
6. Restricted Target List (RTL)
7. Fire Support Coordinating Measures (FSCMs)
8. Situational awareness (SA) on available assets

Phase: The target step begins with validating the confirmed target complies with guidance, LOAC, ROE, and other restrictions. The desired effect against the confirmed target is finalized, restrictions are resolved, and risk assessment is performed. De-confliction of sensors and weapon systems enables weapon-target pairings (WTPs) and generation of potential engagement option. Once the target approval decision is made, an engagement option is selected. Assessment requirements are determined and the consequences of executing the engagement option are also predicted.

Output: The outputs of the target step include the validated desired effect, target data finalized in a format for use by the engaging system, asset deconfliction and resolved target area clearance, and target execution approval, assessment collection requirements, and consequences of execution.

ENGAGE

Input: Inputs to the engage step are the target approval decision, the selected engagement option, and the finalized data of the confirmed target.

Phase: During the engage step, engagement of the confirmed target is ordered and passed to the selected weapon system(s).

Output: The output of the engage step is the engagement of the confirmed target.

ASSESS

Input: The inputs to the assess phase are the combat assessment requirements, the validated desired effect, and the prediction of the consequences of execution.

Phase: During the assess phase information concerning the information is collected in accordance with the combat assessment requirements. The information is

used to estimate or confirm whether the results of the engagement match the desired effect(s). Information is also collected to determine if any consequences of the engagement require warning friendly forces.

Output: Outputs of the assess phase are engagement results; re-attack (re-strike) recommendations, as appropriate; and any warnings to friendly forces based on engagement results.

Figure 38. Dynamic Targeting Process [from JP 3-60, 2007: Ch II, 14]

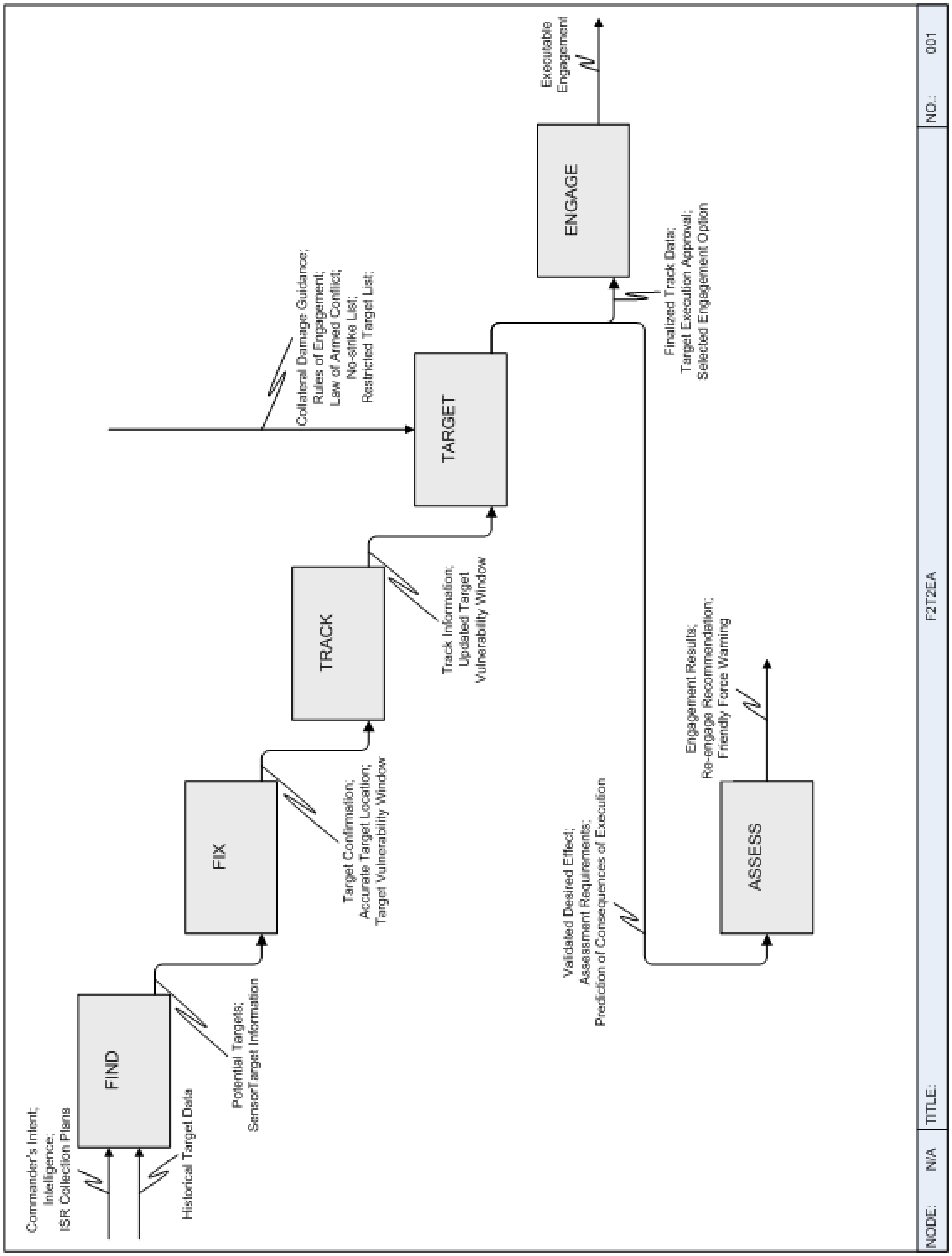

Figure 39. Dynamic Targeting Process – IDEF0
[after JP 3-60, 2007: Ch II, 14]

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APPENDIX C: EXTERNAL SYSTEMS DIAGRAM

The discussions within this appendix are divided into four sections. The first section is devoted to discussing the challenge in developing the basic external systems diagram. The second section presents the basic external systems diagram and the reasons behind key contents of the diagram. The third section is a collection of the interaction diagrams developed during research. Finally, the fourth section is a presentation of the external systems diagram.

A. THE PHILOSOPHICAL CHALLENGE

Recall from the body of the thesis that the basic external systems diagram is comprised of three parts: the system, the external systems, and the system context. The system is "a set of components (subsystems, segments) acting together to achieve a set of common objectives via the accomplishment of a set of tasks" [Buede, 2000: 38]. External Systems are "entities that interact with the system via the system's external interfaces" [Buede, 2000: 38]. Finally, the context is "a set of entities that can impact the system but cannot be impacted by the system" [Buede, 2000: 38].

Since the purpose of the external systems diagram, and therefore the basic external systems diagram, is to define the boundaries of the system for all stakeholders of the system, the author was faced with the question of “What comprises a C2 system?” This question is critical in the development of the operational concept. The question also exemplifies how the key phases of the operational concept development (e.g., scenario development, external systems diagram, systems objective hierarchy, and requirements generation) are intertwined.

Describing the inputs and outputs in the scenario development demonstrates the stakeholders’ and systems engineers’ preconceived notions of the system’s boundaries. Additionally, as the stakeholders and systems engineers communicate concerning the “value” of the system during the system objective hierarchy development, the common view of the system’s boundaries may change. Each phase of the operational concept development serves as feedback to previous phases. With sufficient iterations and

communication, the systems engineers can eventually reach a stable (though not necessarily constant) view of the system. For example, during the communication deriving the "value" of the system in the system objective hierarchy certain subsystems became viewed as external systems and vice versa in a new version of the external systems diagram. This reorganization of components then drove the scenarios and interaction diagrams to be redrafted since the inputs and outputs of the system changed. But, the question still remains, "What comprises a C2 system?"

To answer this question the author conducted an extensive, but by no means exhaustive, literature review. Historical texts, recent articles and books, and service publications were read and analyzed. Much of the historical texts contained discussions on war and its principles as well as theories and methodologies of conducting warfare. The texts, however, contained limited content devoted specifically to topics correlating to the modern concept command and control. Significant research concerning the principles of command and control only began within the past half-century. Much of this early work on a theory of command and control was based on models of the C2 process such as Lawson's [1981] *Sense-Process-Compare-Decide-Act* model or Boyd's *Observe-Orient-Decide-Act* model. To start the definition of a C2 system with a C2 process, whether adopted or modified from previous researchers or developed separately, may seem logical but contains consequences.

Recall that a system is "a set of components (subsystems, segments) acting together to achieve a set of common objectives via the accomplishment of a set of tasks" [Buede, 2000: 38]. A system, therefore, is defined by 1) its set of objectives and 2) the tasks required to achieve such set of objectives. The execution of the C2 process becomes the objective of a C2 system and the tasks required to achieve this objective are at least the phases of the C2 process. For example, the tasks required to achieve the objective in Lawson's model are at least to *sense*, *process*, *compare*, *decide*, and *act*.

Continuing the Lawson model example, since one task of the C2 system would be to *decide*, a component or a combination of components of the C2 system must fulfill this task. Therefore, the decision entity – which in most military situations is the commander – is a component of the system. Similarly the sensor which *senses* should be considered

a component of the system. Then should the entity which *acts* also be considered a component? If so, then the *entire military force* involved in a situation *is the C2 system*. The C2 systems engineer is then faced with designing the best military force for a given set of situations, which incidentally is the responsibility of senior military leadership. Of course a commander-in-chief can view himself or herself as a systems engineer but, a subsystem within a military force with the objective of accomplishing the C2 process would then not exist.

The next logical step would then be to consider reversing the previous step and remove those entities which *act* from the concept of the C2 system definition. In other words, the C2 system's purpose would remain the accomplishment of the C2 process but, the task of *acting* would be fulfilled by a system external to the C2 system. Similarly those sensors which *sense*, and those decision-making entities which *decide*, could be removed from the concept of a C2 system for the same reason and their tasks could be fulfilled by external systems. Continuing this process generates a C2 system with the task of *connecting* the tasks (i.e., *sense*, *process*, *compare*, *decide*, and *act*) of the external systems. A C2 system, therefore, is at least a communication system (a system which *connects*) and at most the entire military force.

As is evident in the above discussion, the definition of a C2 system has now become detached from the C2 process. The system is at least comprised of components which *connect* but may or may not include those components which perform the tasks associated with the C2 process. This logical discussion has achieved a lower bound to the question, "What comprises a C2 system?" It, however, has not achieved a realistic upper bound. An astute reader may have, at this point, realized that the entire discussion above for determining the boundaries of the C2 system progressed through the tasks (or functions) of the system. How can this be? The operational concept is supposed to be an input to the functional architecture. The reader is then plagued by the philosophical question of "How does one define the boundaries of a system in ignorance of what the system does?" The fact of the matter is one does not.

What, then, comprises a C2 system? The answer to the question is confusingly simple – what the systems engineer and stakeholders determine. As systems engineers

communicate with stakeholders, as stakeholders are added and dropped, and as the system engineering process is followed from the birth to the death of the system, the definition of what the system is changes. Therefore, the basic external systems diagram below, and the subsequent work of this thesis, presents a C2 system from the view of the author and those solicited stakeholders whom interacted with the author. It is by no means a definitive solution. As readers join the study and analysis of C2, the definition of what a C2 system is will invariably change.

B. BASIC EXTERNAL SYSTEMS DIAGRAM

The basic external systems diagram developed, as of the submittal of this thesis, is presented in Figure 40. Also presented in this section are key thoughts of the author and ideas gleaned from the author's communication with stakeholders. Though by no means comprehensive, the author has attempted to address the major concerns of potential readers.

As in discussed in Chapter II, the author adopted the concept of function-process-system for command and control. First, command is a function by which a responsible entity takes inputs to produce the desired output. Second, command and control is the process by which the inputs generate the outputs. Finally, a command and control system is the means by which the process is executed. This function-process-system concept is similar to that presented by Sweeney [2002] but, with at least one major modification. Sweeney posits that the command and control process is comprised of people, information, and organization. The author, instead, posits that people are a component of the command and control system, information is what flows within the system, and organization is a rule or constraint on the system. This version of the concept incorporates ideas of Van Creveld [1985], the U.S. Marine Corps [MCDP 6, 1996], and the U.S. Navy [NDP 6, 1995] among many. This can be seen with the two major subsystem categories in Figure 40. , *People* and the *Communications & Information Systems*. The inputs to and outputs from the system, along with the cross-communication between subsystems, are *Information*.

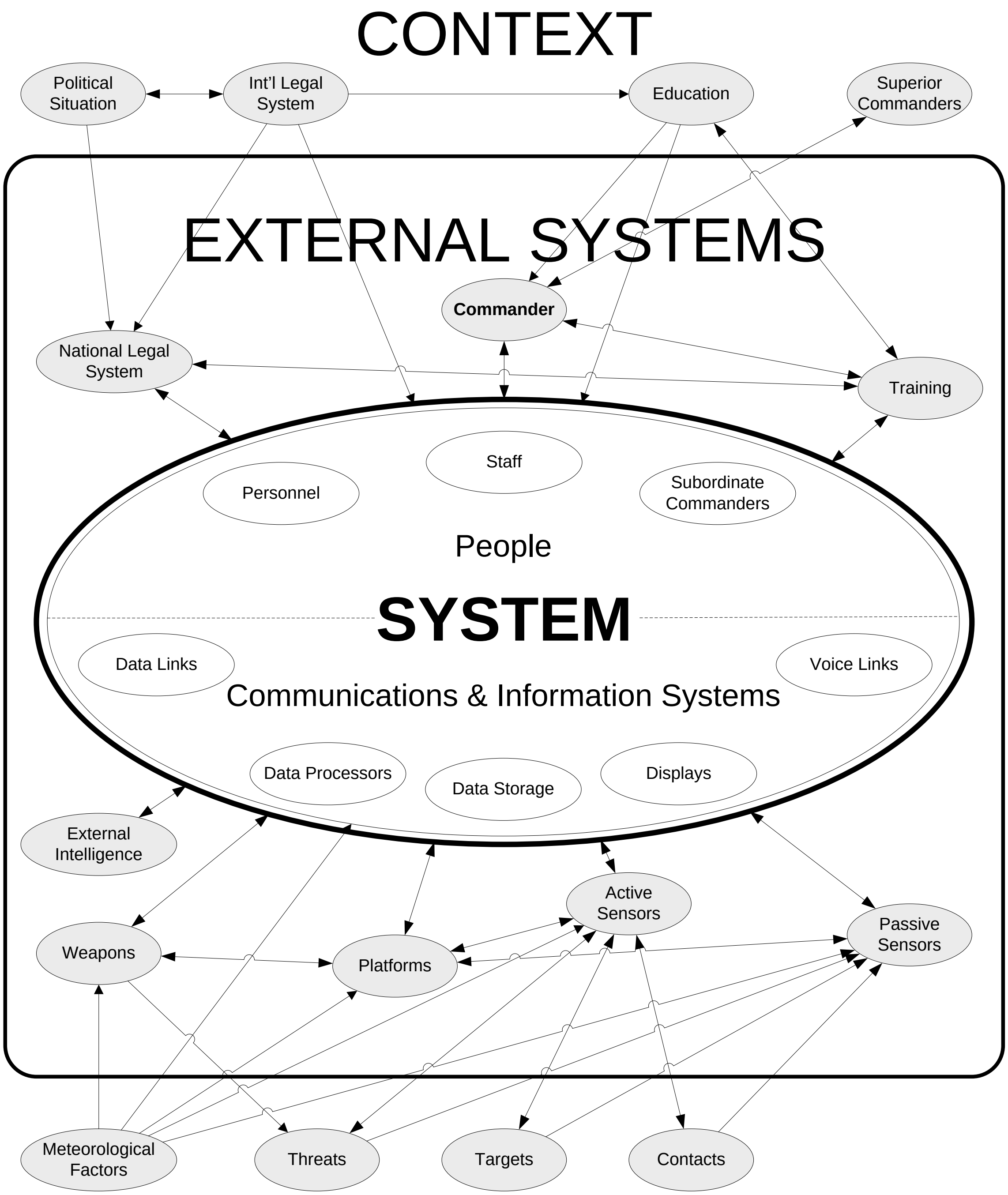

Figure 40. Basic External Systems Diagram

The commander, in this case the OTC, is not considered a part of the command and control system. Since the command and control system is the means by which the command and control process executes the function of command for the commander, the commander is not a component of system. The commander is an external system which

affects the command and control process and interacts with the command and control system. If during the command and control process a decision by the commander is needed, such decision is an input to the command and control system.

Sensors, weapons, and platforms are considered external systems. These external systems provide inputs such as their geographical position, readiness, and in the case of sensors information concerning contacts, targets, threats, and the adversary. During the command and control process a sensation by a sensor is needed, such sensation is an input to the command and control system. Similarly, during the command and control process an action by a weapon or platform is needed, the order for the action is an output from the system to the weapon or platform. Additionally, contacts, targets, threats, and the adversary interact with external systems such as sensors and weapons, which then report to the command and control system information of such interaction. Other context entities produce inputs to the system but are not affected by the command and control system, at least in the time-frame considered for this thesis. Such context entities include meteorological factors, the political situation, and the international legal system.

C. INTERACTION DIAGRAMS

Below is a collection of interaction diagrams developed in support of the external systems diagram.

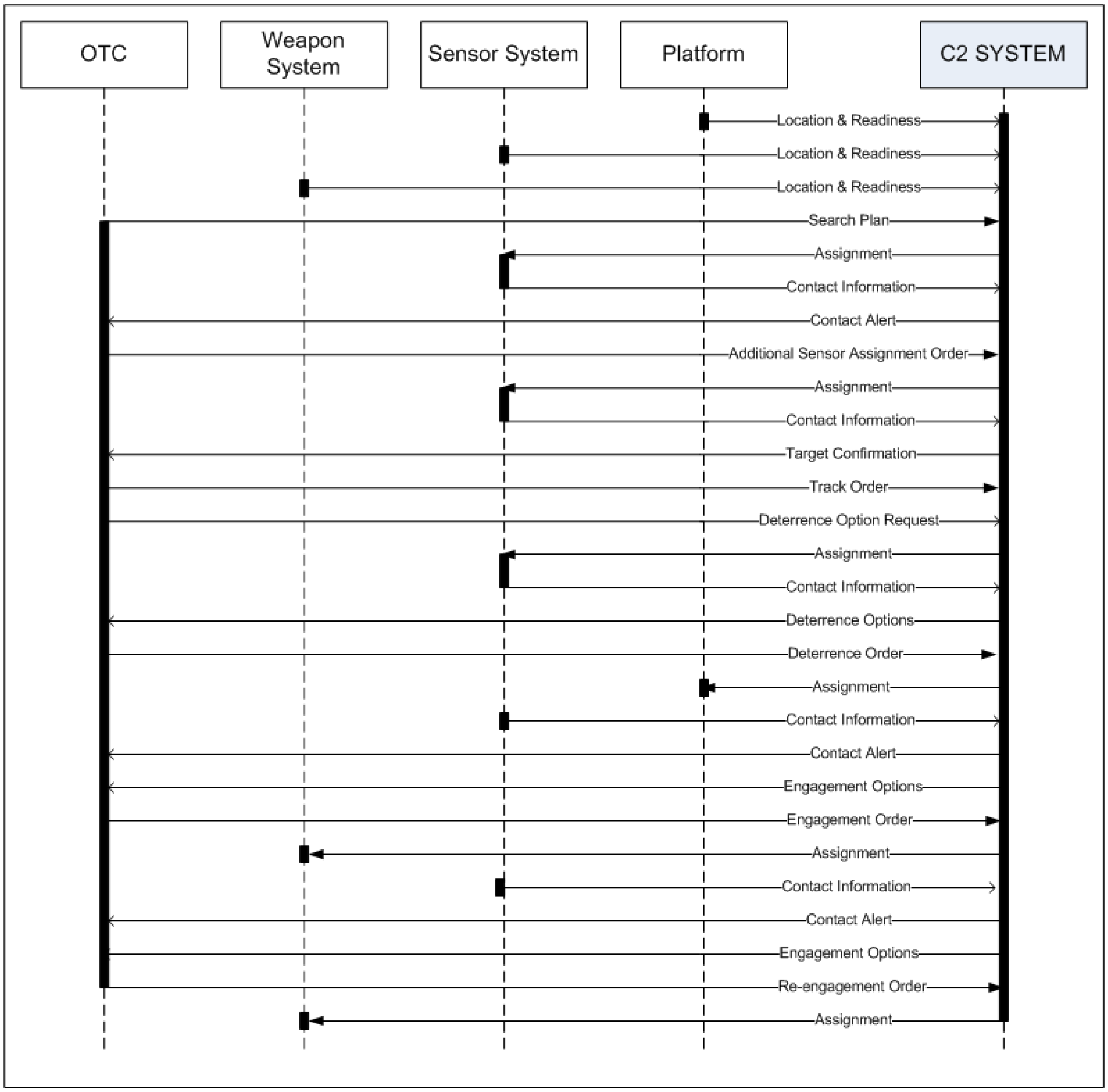

Figure 41. Interaction Diagram –Contact Prosecution

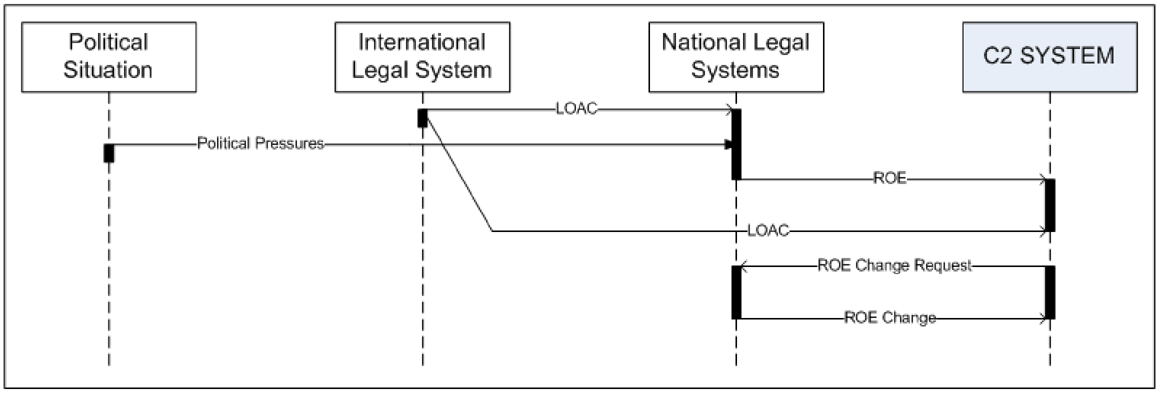

Figure 42. Interaction Diagram – Legal Constraints

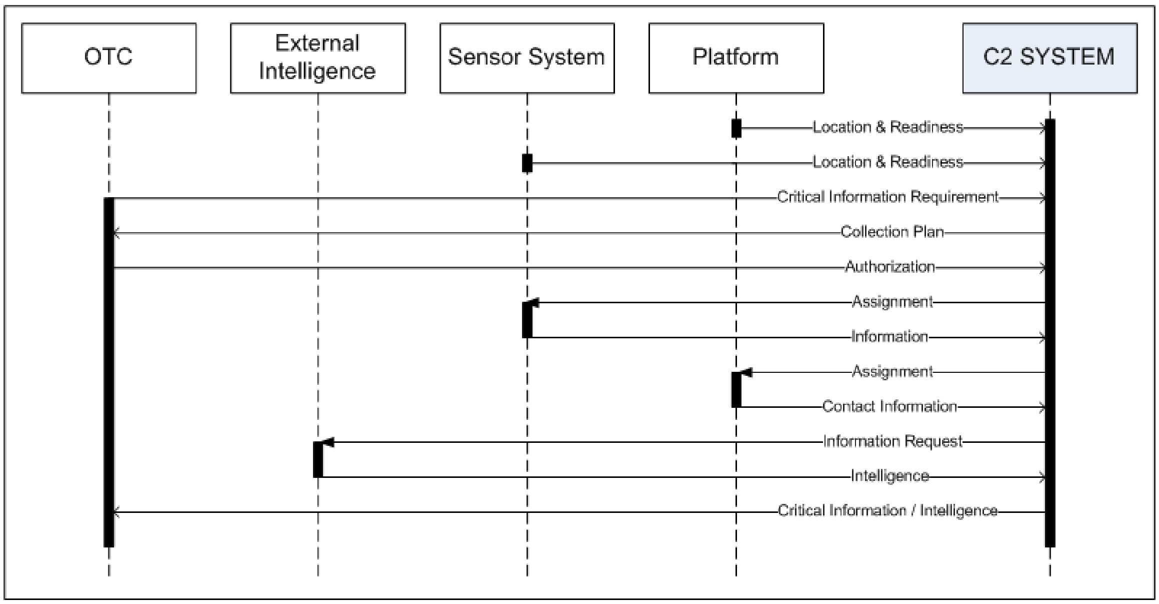

Figure 43. Interaction Diagram – Information and Intelligence Requests

D. EXTERNAL SYSTEMS DIAGRAM

The external systems diagram expands the basic external systems diagram to include the inputs and outputs detailed in interaction diagrams. The purpose of the external systems diagram is to model the "interaction of the system with other (external) systems in the relevant contexts, thus providing a definition of the system's boundaries in terms of the system's inputs and outputs" [Buede, 2000: 144]. The external systems diagram is shown in Figure 44.

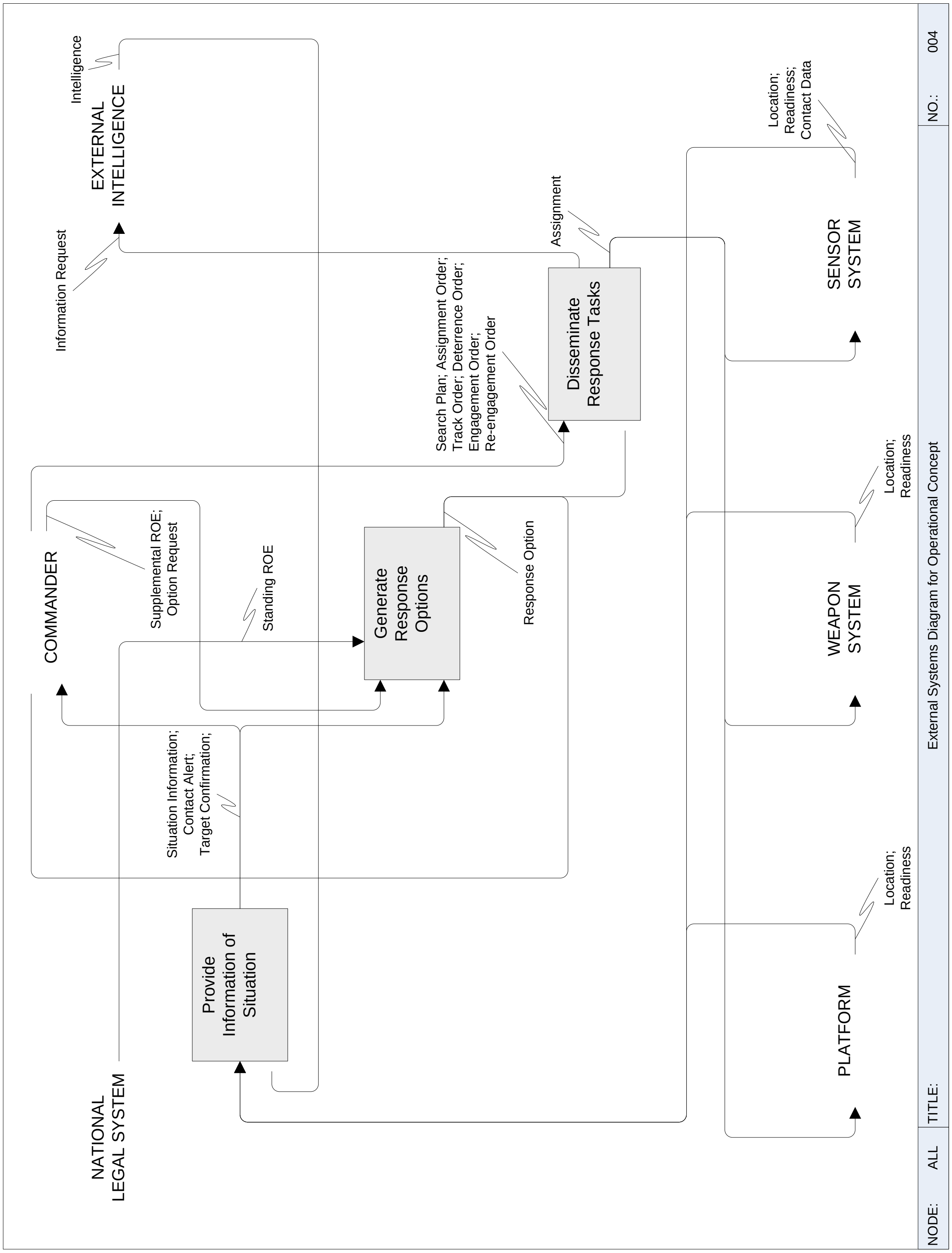

Figure 44. External Systems Diagram

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APPENDIX D: SYSTEM OBJECTIVES HIERARCHY

The purpose of the systems objectives hierarchy is to organize the system's objectives from the view of value to the stakeholders [Buede, 2000: 147]. Objectives exist in every phase of the system's life-cycle. Types of objectives can include operational performance objectives, technical performance objectives, operational suitability objectives, cost objectives, schedule objectives, and risk objectives. The discussions within this appendix are divided into three sections. The first section is devoted to discussing the process of developing the system objectives hierarchy. The second section presents the system objectives. Finally, the third section presents the selected measures of merit.

A. SYSTEM OBJECTIVES DEVELOPMENT

The purpose of the system engineering process is to design and develop a system which takes inputs to produce desired outputs or to avoid undesirable consequence. The entire notion of desirability is one of value [Keeney, 1992]. The purpose of system objectives is to explicitly describe the value of the system as determined by the system's stakeholders. The top-level of the hierarchy of objectives are fundamental objectives which describe the values of the system which are essential. The fundamental objectives are composed of subordinate objectives which serve as measures of merit of the system.

The system objective development process began with the refined problem statement, developed during scenario development, serving as a guide. Keeney [1992: 56] proposes that "The most obvious way to identify objectives is to engage in a discussion of the decision situation." Since publication research is a form of discussion, as Booth, Colomb and Williams contend [2008: 11], numerous publications concerning measures of effectiveness, operational suitability, C4ISR system capabilities, communications, information theory, and network-centric warfare were reviewed to determine qualities pertinent to a network-centric naval tactical command and control system. In conjunction with the publication review, inputs from stakeholders were solicited to assist the author developing and organizing the system's objectives and their

associated measures of merit (i.e., measures of effectiveness and their associated measures of performance) [Buede, 2000: 146-149]. Objective development during the early stages of the systems engineering process is important. By developing a set of system objectives prior to the functional architecture and physical architecture development phases, the system engineer identifies the value of the system outside the constraints of any particular design. The reader is encouraged to review Keeney [1992] for more discussion on this topic.

Reviewing a variety of publications, and with stakeholder input, the author determined there were six fundamental objectives: quality of information; quality of relationships/connections; awareness of established intent; awareness of rules and constraints; quality of response; and quality of allocations. The first four fundamental objectives, together, address the concept the quality of situational awareness. Likewise, the last two fundamental objectives, together, address the concept of quality of response. The top-level of the system objectives hierarchy, which is comprised of the fundamental objectives (FO) and the measures of C2 effectiveness (MoCE), is presented in Figure 45.

Each of the fundamental objectives is an aggregation of several measures of merit (MoM) [NATO Research and Technology Organization, 2002] collected from and developed during the publication review and stakeholder solicitation. Since the focus of this thesis was on naval tactical forces tasked with securing local sea control, Measures of Policy Effectiveness (MoPE), were not considered. Additionally, Measures of Force Effectiveness (MoFE) were not considered since mission accomplishment is not a measure of the C2 system but rather the force. The removal of mission accomplishment from the quality measure of a C2 system is an idea further discussed by Alberts and Hayes [2006: Chapter 4].

The MoM levels considered for this thesis included Measures of C2 Effectiveness (MoCE), Measures of Performance (MoP), and Dimensional Parameters (DP). MoCE focus on the impact of C2 systems within the operational context. MoP measure the performance within the system structure. Finally, the lowest level, Dimensional Parameters (DP), measure the properties or characteristics inherent in the physical parts

and configuration items of the C2 systems. It is a general rule that a measure higher in the MoM hierarchy tends to be more context, task, or mission specific [NATO Research and Technology Organization, 2002: 96].

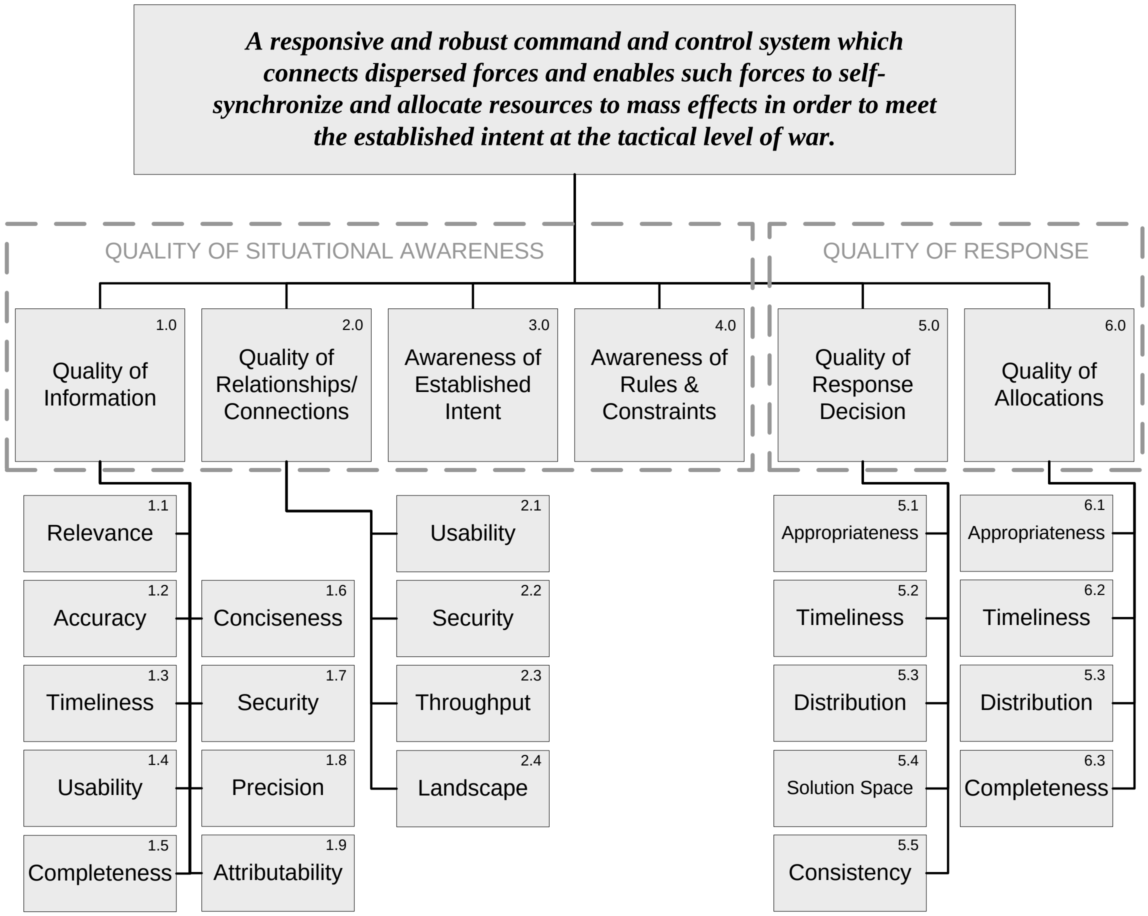

Figure 45. System Objectives Hierarchy

To ensure the system objectives hierarchy did not become an ad hoc collection of objectives and measures gleaned from various sources, the nine desirable attributes of fundamental objectives presented by Keeney [1992: 82-87] were used as a guide during development. The descriptions of the nine attributes were adapted to the system engineering process, as described below, and were adopted whenever possible for this thesis. First, the fundamental objectives of the system should be *essential* to the design of the command and control system; each alternative design of the command and control system impacts the degree to which the fundamental objectives are achieved. Second, the fundamental objectives of the system should be *controllable*; the fundamental objectives

are impacted only by the alternative designs of the command and control system. Third, the set of fundamental objectives of the system should be *complete;* the alternative designs of the system can be differentiated from each other by the set of fundamental objectives. Fourth, the fundamental objectives of the system should be *measurable*; each of the fundamental objectives, and the degree to which they can be achieved, can be precisely defined. Fifth, the fundamental objectives should be *operational*; information can be collected which link the various levels of the fundamental objectives to value of the system. Sixth, the set of fundamental objectives of the system should be *decomposable*; the impact of one fundamental objective can be considered independently of another fundamental objective. Seventh, the fundamental objectives of the system should be *non-redundant*. Eighth, the set of fundamental objectives of the system should be *concise*. Conciseness conflicts with the attribute of completeness, however, by eliminating objectives which provide little assistance in comparing alternative systems the decision scope is reduced. Ninth, each of the fundamental objectives must be *understandable*; the idea of each fundamental objective can be "adequately communicated to and understood by individuals in positions to make or influence decisions" [Keeney, 1992: 85].

Attributes of Fundamental Objectives		
Essential	Controllable	Complete
Measurable	Operational	Decomposable
Non-redundant	Concise	Understandable

Table 19. Attributes of Fundamental Objectives [Keeney, 1992]

The first step to ensuring the set of fundamental objectives were *essential* was to review the previous products of the operational concept. As discussed in Appendix C:

External Systems Diagram the C2 system contains communication and information systems which connect nodes and information flows through these connections. Therefore, quality of information and quality of relationships and connections are *essential*. Quality of relationships and connections was also *essential* because of the portion of the refined problem statement; "command and control system

which connects dispersed forces." The refined problem statement also states the C2 system should enable forces to "allocate resources… in order to meet established intent…." Therefore, awareness of established intent and quality of allocations are also *essential*. Recall, as discussed in Chapter II, that a C2 system is the means by which the C2 process is executed. Therefore, the third step to ensure the set of fundamental objectives were *essential* was to review several conceptual models of the C2 process. Conceptual models reviewed included Lawson [1981], Athans [1986], Levis and Athans [1992], Alberts and Hayes [2006], as well as those presented in NDP 6 [1995] and JP 3-60 [2007]. Though these conceptual models are "abstractions and idealizations" [Levis & Athans, 1992: 6], they do provide examples of what C2 systems are expected to support. All of the conceptual models reviewed describe a phase of the C2 process consists of a decision or decision-making. Therefore, quality of response decision is also an *essential* objective. In addition, all of the conceptual models reviewed describe a phase of the C2 process which consists of actions of forces or directions to forces to act. Since these forces act within an environment and are subject to rules and constraints, whether self-imposed or imposed by higher authority, awareness of rules and constraints is also an *essential* objective. The discussion above has demonstrated that each of the six fundamental objectives is *essential* to the design of a C2 system. The next step is to determine if the set of fundamental objectives is *complete*.

A C2 system is the means by which the C2 process is executed. Therefore, every phase of the C2 process should either have a corresponding objective or it should be explicitly stated why it does not. Several C2 process conceptual models will be used to determine if the set of fundamental objectives are *complete*. Lawson [1981] presents a model simplified as *sense-process-compare-decide-act*. Levis and Athans [1992] present a similar model simplified as *sense-assess-generate-select-plan-direct*. In the external systems diagram, sensors are considered external systems which provide information to the C2 system. Therefore, quality of information corresponds to the concept of *sense*. Some of the MoM of quality of information correspond to *process* and *assess* (i.e., the concepts of accuracy, usability, completeness, and precision allude to a form of assessment of processed data). In addition, awareness of established intent and

awareness of rules and constraints incorporate portions of *assess*. Some of the MoM of quality of response decision and quality of allocations correspond to *generate* (e.g., response solution space) and *select* (e.g., appropriateness of response decision). In addition, the concepts of *decide* and *plan* are also incorporated in these two fundamental objectives. Sensors, weapons, and platforms are external systems which receive information from the C2 system. Therefore, quality of information corresponds to the concepts of *direct* and *act*.

The models presented by Athans [1986] and in JP 3-60 [2007] are specific to target engagement and discussed in Appendix B: Target Engagement. In fact, the models presented by Athans and in JP 3-60 are so specific, and the concepts within the objectives hierarchy so general (e.g., response, allocation, etc.) that it is difficult to determine if the objectives hierarchy does not incorporate all of the concepts of these models. A review of Appendix B: Target Engagement identified only a few concepts not already obviously addressed with the Lawson model and Levis and Athans model analysis above. These concepts include prioritizing ISR, tracking, target area clearance, and risk assessment. Prioritizing ISR is a decision to allocate of resources. Quality of response decision and quality of allocations, therefore, correspond to prioritizing ISR. Tracking is continuous sensing, processing, and assessing. Thus, as discussed above, some of the MoM of quality of information correspond to tracking. Target area clearance is directing friendly forces to vacate a specific area for their safety. Therefore, the allocation of roles and responsibilities addresses target area clearance. Finally, risk assessment corresponds to appropriateness of response decision. The discussion in the previous paragraphs has demonstrated that the set of fundamental objectives is, to an arguable extent, *complete*. Given that there are only six fundamental objectives, the author contends that the set is also *concise*.

The fundamental objectives are *measureable* in the fact that they are aggregations of several MoM collected from and developed during the publication review and stakeholder solicitation. Defoe [1993] states, "Select criteria that are measurable (objective and quantifiable) and express them in well-known, easily understood units. However, important criteria for which no measure seems to exist, still must be explicitly

addressed.” The set of fundamental objectives is *essential* and *complete*; following Defoe’s principle of measurability, no fundamental objective was removed if their associated MoM are difficult to measure. In fact those objectives which are difficult to measure align with the moral factors of command and control, as discussed in Chapter II. Overview of Command and Control

In addition to the attributes previously discussed, the fundamental objectives should also be *operational*. In other words, information should exist which proves the fundamental objectives give value to the system. Validating each fundamental objective and its associated MoM with extensive testing, analysis, or research, was beyond the scope of this thesis. The validity of the fundamental objectives, therefore, is determined by the fact that most were identified in other publications concerning C2 or were in fact specifically referenced in previous C2 research. Next, given that the author cannot guarantee that the system objectives are *understandable*, stakeholders were solicited during the development to mitigate future problems of misunderstanding. Finally, it is left to the reader to analyze the system objective hierarchy in the next section to conclude for themselves whether the systems objectives are *decomposable* (e.g., independent) and *non-redundant*.

B. SYSTEMS OBJECTIVES HIERARCHY

The system objectives hierarchy, with measures of merit, developed during this thesis for a command and control system is presented below in Table 20.

		QUALITY OF SITUATIONAL AWARENESS	
1.0	**FO**	**Quality of Information**	
1.1.	MoCE	Relevance of information	Clark & Moon, 2000 JP 6-0, 2006: Ch I, 3 NDP 6, 1995: 40
1.1.1	MoP	Percentage of processed information needed by nodes for response to changing circumstances	
1.1.2	MoP	Percentage of information a node receives which is a copy of information the node has already received	
1.1.3	MoP	Percentage of information within the network which is a copy of other information within the network	
1.2	MoCE	Accuracy of information	JP 6-0, 2006: Ch I, 3 NDP 6, 1995: 40

1.2.1	MoP	Number of sources confirming information	Clark & Moon, 2000: Section 6
1.2.2	MoP	Veracity (i.e., truthfulness) of sources	Clark & Moon, 2000: Section 6
1.2.2.1	DP	History of truthfulness of specific source	
2.2.2.2	DP	Probability specific source is telling the truth concerning selected piece of information	
1.2.3	MoP	Equivocality of information (i.e., degree to which data is subject to two or more interpretations)	
1.2.3.1	MoP	Number of possible interpretations of data	
1.2.3.2	MoP	Probability interpretation of data is correct	
1.2.4	MoP	Internal consistency of information	Clark & Moon, 2000: Section 6
1.2.4.1	MoP	Percentage of total information held which conflicts with other information held	Clark & Moon, 2000: Section 6
1.2.4.2	MoP	Mean time between internal inconsistencies of information held	
1.3	MoCE	Timeliness of information	Cebrowski & Garstka, 1998 Clark & Moon, 2000 JP 6-0, 2006: Ch I, 3 NDP 6, 1995: 40 Stytz & Banks, 2006
1.3.1	MoP	Time between changing circumstances and observation	after Alberts & Hayes, 2006: 43 after Kasunic & Anderson, 2004: 39
1.3.2	MoP	Time between the observation and the completion of processing the data into information	after Kasunic & Anderson, 2004: 39
1.3.3	MoP	Frequency (i.e., refresh-rate) of information	Clark & Moon, 2000: Section 6
1.3.3.1.1	MoP	Minimum time specific piece of information is updated	
1.3.3.1.2	MoP	Mean time specific piece of information is updated	
1.3.3.1.3	MoP	Median time specific piece of information is updated	
1.3.3.1.4	MoP	Maximum time specific piece of information is updated	
1.3.4	MoP	Perishability (i.e. shelf-life) of information	Clark & Moon, 2000: Section 6
1.3.4.1	DP	Shelf-life of specific information	
1.3.4.2	MoP	Difference between shelf-life and minimum time specific information is updated	
1.3.4.3	MoP	Difference between shelf-life and maximum time specific information is updated	
1.3.4.4	MoP	Probability of shelf-life is less then time between updates	
1.3.5	MoP	Differential between time when information is needed by a particular force and time when it arrives at that force	Stytz & Banks, 2006
1.4	MoCE	Usability of information	JP 6-0, 2006: Ch I, 3 NDP 6, 1995: 40
1.4.1	MoP	Latency (i.e., visibility) of information	Clark & Moon, 2000: Section 6
1.4.1.1	MoP	Number of nodes which are capable of viewing information	
1.4.1.2	MoP	Percentage of nodes which are capable of viewing information	
1.4.1.3	MoP	Percentage of nodes, which are capable of using information, that can view the information	

1.4.2	MoP	Shareability of information (i.e., ability of information to be used by multiple nodes)	NATO Research and Technology Organization (R&TO), 2006: 21
1.4.2.1	MoP	Percentage of nodes authorized to act upon information	after Washburn, 2001a: 6
1.4.2.2	MoP	Percentage of nodes which are capable of acting on information	
1.5	MoCE	Completeness of information	Clark & Moon, 2000 JP 6-0, 2006: Ch I, 3 NDP 6, 1995: 40
1.5.1	MoP	Range (i.e., scale) of observation capability	
1.5.1.1	DP	Spatial range of observation capability	
1.5.1.2	DP	Temporal range of observation capability	
1.5.2	MoP	Availability of information	after Alberts & Hayes, 2006: 58
1.5.2.1	MoP	Proportion of collected information which was processed	Clark & Moon, 2000: Section 6
1.5.2.2	MoP	Percentage of Commander’s Critical Information Requirements (CCIR) met	after Clark & Moon, 2000: Section 6
1.5.2.3	MoP	Percentage of Priority Intelligence Requirements (PIR) met	
1.5.2.4	MoP	Percentage of Essential Elements of Information (EEI) met	
1.5.2.4.1	MoP	Percentage of EEI from PIR met	
1.5.2.4.2	MoP	Percentage of EEI from RFI met	
1.5.2.5	MoP	Percentage of commander’s Essential Elements of Friendly Information (EEFI) met	
1.5.2.6	MoP	Percentage of Requests for Intelligence (RFI) met	
1.6	MoCE	Conciseness (i.e., brevity) of information	JP 6-0, 2006: Ch I, 3
1.6.1	MoP	Size (bytes) of digitized data	
1.6.1.1	DP	Size of digitized datum	
1.6.1.2	MoP	Mean size of all digitized data	
1.6.1.3	MoP	Median size of all digitized data	
1.6.1.4	MoP	Maximum size of all digitized data	
1.6.2	MoP	Time of analog data (e.g., spoken voice)	
1.6.2.1	DP	Time of analog datum	
1.6.2.2	MoP	Mean time of all analog data	
1.6.2.3	MoP	Median time of all analog data	
1.6.2.4	MoP	Maximum size of all analog data	
1.7	MoCE	Security of information	JP 6-0, 2006: Ch I, 3
1.7.1	MoP	Probability of detection of specific information traversing the network of relationships and connections	after JP 6-0, 2006: Ch I, 10
1.7.2	MoP	Probability of interception of specific information traversing the network of relationships and connections	after JP 6-0, 2006: Ch I, 10
1.8	MoCE	Precision of information	NDP 6, 1995: 40
1.8.1	MoP	Resolution of observation capability	after NATO R&TO, 2006:17
1.8.1.1	DP	Spatial resolution of observation capability	
1.8.1.2	DP	Temporal resolution of observation capability	
1.8.2	MoP	Repeatability of observation capability (i.e., similarity of observations taken under same conditions)	

1.8.2.1	MoP	Range of differences in observations under same conditions	
1.8.2.2	MoP	Deviation of observations under same conditions from the mean	
1.9	MoCE	Attributability (i.e., pedigree) of information	NATO R&TO, 2006: 18
1.9.1	MoP	Differential between time information is received by a node and when information can be attributed	
1.9.2	MoP	Number of nodes in the life of the information to which it can be attributed	
1.9.3	MoP	Specificity of a nodes identity	
2.0	**FO**	**Quality of relationships/connections**	
2.1	MoCE	Usability of relationships and connections	
2.1.1	MoP	Availability of needed relationships and connections	
2.1.1.1	MoP	Percentage of total known sources that are available via existing relationships and connections	after Clark & Moon, 2000: Section 6
2.1.1.2	MoP	Percentage of total decision-authorized entities that are available via existing relationships and connections	
2.1.1.3	MoP	Percentage of total allocation-authorized entities that are available via existing relationships and connections	
2.1.1.4	MoP	Percentage of total action-authorized entities that are available via existing relationships and connections	
2.1.1.5	MoP	Time between failures to have needed relationships and connections	
2.1.2	MoP	Reliability of relationships and connections	
2.1.2.1	MoP	Duration of operational failure-free connections	
2.1.2.1.1	DP	Time between operational failures for each connection	
2.1.2.1.2	MoP	Time between operational failures for the network of connections	
2.1.2.2	MoP	Probability of operational failure-free connections	
2.1.2.2.1	DP	Probability of operational failure for each connection	
2.1.2.2.2	MoP	Probability of operational failure for network of connections	
2.1.3	MoP	Veracity (i.e., accuracy of transmission) of needed relationships and connections	
2.1.3.1	MoP	Duration of error-free transmissions	
2.1.3.1.1	DP	Time between transmission error for each connection	
2.1.3.1.2	MoP	Time between transmission error for the network of connections	
2.1.3.2	MoP	Probability of error-free transmissions	
2.1.3.2.1	DP	Probability of error-free transmission for each connection	
2.1.3.2.2	MoP	Probability of error-free transmission for the network of connections	
2.1.4	MoP	Utilization of relationships and connections	after Kasunic & Anderson, 2004: 39
2.1.4.1	MoP	Frequency of utilization	

2.1.4.1.1	MoP	Number of uses per unit time of each relationship and connection	
2.1.4.1.2	MoP	Mean number of uses per unit time of relationships and connections	
2.1.4.1.3	MoP	Median number of uses per unit time of relationships and connections	
2.1.4.2	MoP	Duration of utilization	
2.1.4.2.1	MoP	Mean duration of use of each relationship and connection	
2.1.4.2.2	MoP	Median duration of use of each relationship and connection	
2.1.4.2.3	MoP	Minimum duration of use of each relationship and connection	
2.1.4.2.4	MoP	Mean duration of use of all relationships and connections	
2.1.4.2.5	MoP	Median duration of use of each relationship and connection	
2.1.4.2.6	MoP	Maximum duration of use of each relationship and connection	
2.2	MoCE	Security of relationships and connections	
2.2.1	MoP	Detection of relationships and connections	
2.2.1.1	MoP	Probability of Detection	
2.2.1.2	MoP	Mean time between known detections by specified entity	
2.2.2	MoP	Detection of information traversing relationship or connection	
2.2.2.1	MoP	Probability of detection of specific relationship or connection	JP 6-0, 2006: Ch I, 10
2.2.2.2	MoP	Mean time between known detections of specific relationship or connection by specified entity	
2.2.3	MoP	Interception of information traversing relationship and connection	
2.2.1	MoP	Probability of interception of information traversing specific relationship or connection	JP 6-0, 2006: Ch I, 10
2.2.2	MoP	Mean time between known interception of information traversing a specific relationship or connection	
2.3	MoCE	Throughput of relationships and connections	
2.3.1	MoP	Capacity of relationships and connections	after Kasunic & Anderson, 2004: 39 after Stytz & Banks, 2006: Section 4
2.3.1.1	DP	Capacity of each relationship and connection	
2.3.1.2	MoP	Capacity of the network of relationships and connections	
2.3.2	MoP	Speed of service the relationships and connections are capable of providing	after Clark & Moon, 2000: Section 6
2.3.2.1	DP	Speed of service each relationship or connection is capable of providing	
2.3.2.2	MoP	Speed of service the network of relationships and connections is capable of providing	
2.3.3	MoP	Overflow of needed relationships and connections	after Kasunic & Anderson, 2004: 39

2.3.3.1	MoP	Quantity of overflow beyond capacity of needed relationships and connections	
2.3.3.1.1	DP	Quantity of overflow beyond capacity for each needed relationship or connection	
2.3.3.1.2	MoP	Quantity of overflow beyond capacity for the network of relationships and connections	
2.3.3.2	MoP	Duration of overflow beyond capacity of needed relationships and connections	
2.3.3.2.1	DP	Duration of overflow beyond capacity for each needed relationship or connection	
2.3.3.2.2	MoP	Duration of overflow beyond capacity for the network of relationships and connections	
2.3.3.3	MoP	Probability of overflow beyond capacity of needed relationships and connections	
2.3.3.3.1	DP	Probability of overflow beyond capacity for each needed relationships or connections	
2.3.3.3.2	MoP	Probability of overflow beyond capacity for the network of needed relationships and connections	
2.4	MoCE	Landscape of the relationships and connections	
2.4.1	MoP	Geographical reach of the relationships and connections	after Clark & Moon, 2000: Section 1
2.4.1.1	MoP	Geographical volume of relationships and connections	
2.4.1.1.1	DP	Geographical volume of each relationship or connection	
2.4.1.1.2	MoP	Mean geographical volume of relationships and connections	
2.4.1.1.3	MoP	Median geographical volume of relationships and connections	
2.4.1.1.4	MoP	Total geographical volume of relationships and connections	
2.4.2	MoP	Reconfigurability, or adaptability, of relationships and connections to meet changing circumstances and/or necessary responses	
2.4.2.1	MoP	Time to reconfigure	
2.4.2.1.1	MoP	Minimum time required to reconfigure relationships and connections to meet changing circumstances and/or necessary responses	
2.4.2.1.2	MoP	Mean time required to reconfigure relationships and connections to meet changing circumstances and/or necessary responses	
2.4.2.1.3	MoP	Median time required to reconfigure relationships and connections to meet changing circumstances and/or necessary responses	
2.4.2.1.4	MoP	Maximum time required to reconfigure relationships and connections to meet changing circumstances and/or necessary responses	
2.4.2.2	MoP	Number of possible solutions for required reconfiguration to meet changing circumstances and/or necessary responses	
2.4.3	MoP	Interoperability of relationships and connections (i.e., ability of relationship or connection to be used by varying types of nodes)	after NATO R&TO, 2006: 20 JP 6-0, 2006: Ch I, 8
2.4.3.1	MoP	Commonality of relationships and connections	JP 6-0, 2006: Ch I, 8

2.4.3.1.1	DP	Number of nodes each relationship or connection is capable of connecting with	
2.4.3.1.2	MoP	Percentage of nodes which each relationship or connection is capable of connecting with	
2.4.3.1.3	MoP	Mean percentage of nodes which each relationship or connection is capable of connecting with	
2.4.3.1.4	MoP	Median percentage of nodes which each relationship or connection is capable of connecting with	
2.4.3.2	MoP	Standardization of relationships and connections	JP 6-0, 2006: Ch I, 8
2.4.3.2.1	MoP	Percentage of interfaces which meet standardization requirements	
2.4.3.2.2	DP	Percentage of interfaces at a node which do not meet standardization requirements	
2.4.3.2.3	MoP	Number of nodes which have at least one interface which does not meet standardization requirements	
2.4.3.2.4	MoP	Percentage of nodes which have at least one interface which does not meet standardization requirements	
2.4.3.2.5	MoP	Number of nodes which have no interfaces which meet standardization requirements	
2.4.3.2.6	MoP	Percentage of nodes which have no interfaces which meet standardization requirements	
2.4.3.3	MoP	Compatibility of relationships and connections (i.e., capability of two or more relationships or connections to exist without mutual interference)	JP 6-0, 2006: Ch I, 8
2.4.3.1	DP	Minimum stand-off distance of interference for each connection	
2.4.3.2	DP	Frequency separation for each connection	
2.4.4	MoP	Extensibility of relationships and connections to meet changing circumstances and/or necessary responses	
2.4.4.1	MoP	Landscape of extension	
2.4.4.1.1	MoP	Number of nodes connection is capable of adding	
2.4.4.1.2	MoP	Number of connections capable of adding a given node	
2.4.4.1.3	MoP	Number of nodes the network of connections are capable of adding	
2.4.4.1.4	MoP	Available connection capacity for each potentially added node	
2.4.4.1.5	MoP	Available total connection capacity for all potentially added nodes	
2.4.4.2	MoP	Time to extend	
2.4.4.2.1	MoP	Minimum time required to add a relationship and connection to meet changing circumstances and/or necessary responses	
2.4.4.2.2	MoP	Mean time required to add a relationship and connection to meet changing circumstances and/or necessary responses	
2.4.4.2.3	MoP	Median time required to add a relationship and connection to meet changing circumstances and/or necessary responses	

2.4.4.2.4	MoP	Maximum time required to add a relationship and connection to meet changing circumstances and/or necessary responses	
2.4.4.2.5	MoP	Minimum time required to add all relationships and connections to meet changing circumstances and/or necessary responses	
2.4.4.2.6	MoP	Mean time required to add all relationships and connections to meet changing circumstances and/or necessary responses	
2.4.4.2.7	MoP	Median time required to add all relationships and connections to meet changing circumstances and/or necessary responses	
2.4.4.2.8	MoP	Maximum time required to add all relationships and connections to meet changing circumstances and/or necessary responses	
2.4.5	MoP	Mobility of nodes	NATO R&TO, 2006: 17
2.4.5.1	MoP	Geographical range of nodes	
2.4.5.1.1	DP	Geographical range each node can maneuver while maintaining needed relationships or connections	
2.4.5.1.2	MoP	Mean geographical range nodes can maneuver while maintaining needed relationships or connections	
2.4.5.1.3	MoP	Median geographical range nodes can maneuver while maintaining needed relationships or connections	
2.4.5.2	MoP	Geographical speed of nodes	
2.4.5.2.1	DP	Geographical speed at which each node can maneuver while maintaining needed relationships or connections	
2.4.5.2.2	MoP	Mean geographical speed at which nodes can maneuver while maintaining needed relationships and connections	
2.4.5.2.3	MoP	Median geographical speed at which nodes can maneuver while maintaining needed relationships and connections	
2.4.5.2.3	MoP	Maximum geographical speed at which nodes can maneuver while maintaining needed relationships and connections	
3.0	**FO**	**Awareness of Established Intent**	
3.1	MoP	Degree to which the established intent is understood by forces	Alberts & Hayes, 2006: 38-39
3.2	MoP	Consistency of established intent between forces	
3.3	MoP	Time differential of awareness of established intent by different forces	
3.4	MoP	Differential in time between awareness of established intent by a force and time when awareness is needed for force to act accordingly	
3.5	MoP	Degree of situational familiarity for forces	NATO R&TO, 2006: 18
4.0	**FO**	**Awareness of Rules and Constraints**	
4.1	MoP	Degree to which rules and constraints are understood by forces	Alberts & Hayes, 2006: 42
4.2	MoP	Consistency of awareness between forces of rules and constraints which are applicable to such forces	

4.3	MoP	Accuracy of awareness of rules and constraints compared with actual rules and constraints	after Alberts & Hayes, 2006: 144
		QUALITY OF RESPONSE	
5.0	**FO**	**Quality of response decision**	
5.1	MoCE	Appropriateness of response to changing circumstances	Alberts & Hayes, 2006: 42
5.1.1	MoP	Degree to which the established intent is accepted by forces	Alberts & Hayes, 2006: 38-39
5.1.2	MoP	Consistency of response with established intent	
5.1.3	MoP	Degree to which rules and constraints are accepted by forces	Alberts & Hayes, 2006: 42
5.1.4	MoP	Consistency of response with rules and constraints	
5.1.5	MoP	Degree of risk to forces for each response	
5.2	MoCE	Timeliness of response decision	after Alberts & Hayes, 2006: 43
5.2.1	MoP	Time between receipt of information concerning changing circumstances and acknowledgement of receipt	
5.2.2	MoP	Time between acknowledgement of receipt of information concerning changing circumstances and response decision	
5.2.2.1	MoP	Time between acknowledgement of receipt of information concerning changing circumstances and response option being developed	
5.2.2.2	MoP	Time between response option being developed and response decision	
5.2.3	MoP	Time between response decision and order of response execution by decision-authorized entity	
5.2.4	MoP	Time between order of response execution and time required to allocate and execute response	
5.3	MoCE	Distribution of response decision capability	
5.3.1	MoP	Mean number of connections between decision-authorized entity and action-authorized entity	
5.3.2	MoP	Median number of connections between decision-authorized entity and action-authorized entity	
5.3.3	MoP	Maximum number of connections between decision-authorized entity and action-authorized entity	
5.3.4	MoP	Percentage of entities connected by existing relationships and connections which are authorized to make a specific decision concerning a specific change in circumstances	
5.4	MoCE	Response solution space	
5.4.1	MoP	Number of distinct response solutions generated by decision-authorized entities concerning a specific change in circumstances	
5.4.2	MoP	Number of distinct response solutions concerning a specific change in circumstances which, if selected concurrently, do not interfere with each other in execution	
5.5	MoCE	Consistency of response between decision-authorized entities	
5.5.1	MoP	Number of action-authorized entities with conflicting orders from decision-authorized entities	

5.5.2	MoP	Percentage of action-authorized entities with conflicting orders from decision-authorized entities	
6.0	**FO**	**Quality of allocations**	
6.1	MoCE	Appropriateness of allocations	
6.1.1	MoP	Degree to which forces understand the roles and responsibilities allocated to them	Alberts & Hayes, 2006: 41
6.1.2	MoP	Degree to which forces accept the roles and responsibilities allocated to them	
6.1.3	MoP	Feasibility of role and responsibility allocations	after NATO R&TO, 2006: 24
6.1.3.1	MoP	Availability of material for allocation	after Alberts & Hayes, 2006: 58
6.1.3.2	MoP	Number of action-authorized entities which are allocated a role or responsibility which they cannot accomplish	
6.1.3.3	MoP	Percentage of action-authorized entities which are allocated a role or responsibility which they cannot accomplish	
6.2	MoCE	Timeliness of allocations	
6.2.1	MoP	Time between order of response execution by decision-authorized entity and completion of allocations by allocation-authorized entity	
6.2.2	MoP	Time between allocation of role or responsibility and commencement of role or responsibility by action-authorized entity	
6.2.3	MoP	Time between allocation of role or responsibility and time required to execute response action	
6.3	MoCE	Distribution of response allocation capability	
6.3.1	MoP	Mean number of connections between allocation-authorized entity and action-authorized entity	
6.3.2	MoP	Median number of connections between allocation-authorized entity and action-authorized entity	
6.3.3	MoP	Maximum number of connections between allocation-authorized entity and action-authorized entity	
6.3.4	MoP	Percentage of entities connected by existing relationships and connections which are authorized to make allocations concerning a specific decision	
6.4	MoCE	Completeness of role and responsibility allocation	Alberts & Hayes, 2006: 41
6.4.1	MoP	Number of roles and responsibilities which are required for the specific decision which are not allocated	
6.4.2	MoP	Percentage of roles and responsibilities which are required for the specific decision which are not allocated	

Table 20. System Objectives Hierarchy

C. SELECTED MEASURES OF MERIT

The focus of this thesis was on the engineering of a command and control system for naval forces at the tactical level of war which could incorporate concepts associated with network-centric warfare. The systems objective hierarchy presented in the previous

section is far too large, given the scope of this thesis, for an effective analysis of the value of the C2 system. Therefore, a reasonable subset of the measures was selected for the remaining phases of the engineering process. The refined problem statement generated during the operational concept development served as a guide for the selection. Recall that the refined problem statement is:

> A responsive and robust command and control system which connects dispersed forces and enables such forces to self-synchronize and allocate resources to mass effects in order to meet the established intent at the tactical level of war.

Responsive is the timeliness in which the command and control system can identify changing circumstances, determine the impact of the changing circumstances, and enact an appropriate response. Selected measures of performance applying to the concept of *responsive* are presented in Table 21.

1.3.1	MoP	Time between changing circumstances and observation
1.3.2	MoP	Time between the observation and the completion of processing the data into information
1.3.4.4	MoP	Probability of shelf-life is less then time between updates
1.9.1	MoP	Differential between time information is received by a node and when information can be attributed
2.4.2.1.3	MoP	Median time required to reconfigure relationships and connections to meet changing circumstances and/or necessary responses
2.4.4.2.7	MoP	Median time required to add all relationships and connections to meet changing circumstances and/or necessary responses
5.2.1	MoP	Time between receipt of information concerning changing circumstances and acknowledgement of receipt
5.2.2.1	MoP	Time between acknowledgement of receipt of information concerning changing circumstances and response option being developed
5.2.2.2	MoP	Time between response option being developed and response decision
5.2.3	MoP	Time between response decision and order of response execution by decision-authorized entity
6.2.1	MoP	Time between order of response execution by decision-authorized entity and completion of allocations by allocation-authorized entity
6.2.2	MoP	Time between allocation of role or responsibility and commencement of role or responsibility by action-authorized entity

Table 21. *Responsive* Measures of Performance

Robust it is meant the ability of the command and control system to identify a range of changing circumstances, determine the impact of the changing circumstances, and enact an appropriate response. Selected measures of merit applying to the concept of *robust* are presented in Table 22.

1.2.1	MoP	Number of sources confirming information
1.5.2.4	MoP	Percentage of Essential Elements of Information (EEI) met
1.5.2.5	MoP	Percentage of commander’s Essential Elements of Friendly Information (EEFI) met
1.8.1.1	DP	Spatial resolution of observation capability
1.8.1.2	DP	Temporal resolution of observation capability
1.9.2	MoP	Number of nodes in the life of the information to which it can be attributed
2.1.2.1.2	MoP	Time between operational failures for the network of connections
2.1.2.2.2	MoP	Probability of operational failure for network of connections
2.3.3.1.2	MoP	Quantity of overflow beyond capacity for the network of relationships and connections
2.4.2.2	MoP	Number of possible solutions for required reconfiguration to meet changing circumstances and/or necessary responses
2.4.3.1.4	MoP	Median percentage of nodes which each relationship or connection is capable of connecting with
2.4.4.1.3	MoP	Number of nodes the network of connections are capable of adding
5.4.1	MoP	Number of distinct response solutions generated by decision-authorized entities concerning a specific change in circumstances

Table 22. *Robust* Measures of Performance and Dimensional Parameters

Dispersed forces are geographically dispersed as well as dispersed on the network which connects the forces. Selected measures of merit applying to the concept of *dispersed forces* are presented in Table 23.

1.4.1.2	MoP	Percentage of nodes which are capable of viewing information
1.4.2.2	MoP	Percentage of nodes which a capable of acting information
2.1.1.2	MoP	Percentage of total decision-authorized entities that are available via existing relationships and connections
2.1.1.3	MoP	Percentage of total allocation-authorized entities that are available via existing relationships and connections
2.1.1.4	MoP	Percentage of total action-authorized entities that are available via existing relationships and connections
2.4.1.1.4	MoP	Total geographical volume of relationships and connections
2.4.5.1.3	MoP	Median geographical range nodes can maneuver while maintaining needed relationships or connections
5.3.2	MoP	Median number of connections between decision-authorized entity and action-authorized entity
5.3.4	MoP	Percentage of entities connected by existing relationships and connections which are authorized to make a specific decision concerning a specific change in circumstances
6.3.2	MoP	Median number of connections between allocation-authorized entity and action-authorized entity
6.3.4	MoP	Percentage of entities connected by existing relationships and connections which are authorized to make allocations concerning a specific decision

Table 23. *Dispersed Forces* Measures of Performance

Self-synchronization is the ability of a force to "organize and synchronize complex warfare activities from the bottom up" [Cebrowski & Garstka, 1998]. *Self-synchronization* includes the ability for the forces to allocate resources at their disposal to *mass effects* to meet an established intent. *Established intent* is used instead of the traditional *commander's intent* since self-synchronizing forces, which either may not be connected with their commander or may not have a commander (e.g., coalition forces), may be capable identifying and responding to emerging circumstances which alter the operating environment and their purpose. Selected measures of merit applying to the concept of *self-synchronization* are presented in Table 24.

3.2	MoP	Consistency of established intent between forces
4.2	MoP	Consistency of awareness between forces of rules and constraints which are applicable to such forces
5.1.2	MoP	Consistency of response with established intent
5.1.4	MoP	Consistency of response with rules and constraints
5.5.2	MoP	Percentage of action-authorized entities with conflicting orders from decision-authorized entities
6.1.3.3	MoP	Percentage of action-authorized entities which are allocated a role or responsibility which they cannot accomplish
6.4.2	MoP	Percentage of roles and responsibilities which are required for the specific decision which are not allocated

Table 24. *Self-synchronization* Measures of Performance

The entire set of selected measures is presented below in Table 25.

1.2.1	MoP	Number of sources confirming information
1.3.1	MoP	Time between changing circumstances and observation
1.3.2	MoP	Time between the observation and the completion of processing the data into information
1.3.4.4	MoP	Probability of shelf-life is less then time between updates
1.4.1.2	MoP	Percentage of nodes which are capable of viewing information
1.4.2.2	MoP	Percentage of nodes which a capable of acting information
1.5.2.4	MoP	Percentage of Essential Elements of Information (EEI) met
1.5.2.5	MoP	Percentage of commander's Essential Elements of Friendly Information (EEFI) met
1.8.1.1	DP	Spatial resolution of observation capability
1.8.1.2	DP	Temporal resolution of observation capability
1.9.2	MoP	Number of nodes in the life of the information to which it can be attributed
1.9.1	MoP	Differential between time information is received by a node and when information can be attributed
2.1.1.2	MoP	Percentage of total decision-authorized entities that are available via existing relationships and connections
2.1.1.3	MoP	Percentage of total allocation-authorized entities that are available via existing relationships and connections
2.1.1.4	MoP	Percentage of total action-authorized entities that are available via existing relationships and connections
2.1.2.1.2	MoP	Time between operational failures for the network of connections
2.1.2.2.2	MoP	Probability of operational failure for network of connections

2.3.3.1.2	MoP	Quantity of overflow beyond capacity for the network of relationships and connections
2.4.1.1.4	MoP	Total geographical volume of relationships and connections
2.4.2.1.3	MoP	Median time required to reconfigure relationships and connections to meet changing circumstances and/or necessary responses
2.4.2.2	MoP	Number of possible solutions for required reconfiguration to meet changing circumstances and/or necessary responses
2.4.3.1.4	MoP	Median percentage of nodes which each relationship or connection is capable of connecting with
2.4.4.1.3	MoP	Number of nodes the network of connections are capable of adding
2.4.4.2.7	MoP	Median time required to add all relationships and connections to meet changing circumstances and/or necessary responses
2.4.5.1.3	MoP	Median geographical range nodes can maneuver while maintaining needed relationships or connections
3.2	MoP	Consistency of established intent between forces
4.2	MoP	Consistency of awareness between forces of rules and constraints which are applicable to such forces
5.1.2	MoP	Consistency of response with established intent
5.1.4	MoP	Consistency of response with rules and constraints
5.2.1	MoP	Time between receipt of information concerning changing circumstances and acknowledgement of receipt
5.2.2.1	MoP	Time between acknowledgement of receipt of information concerning changing circumstances and response option being developed
5.2.2.2	MoP	Time between response option being developed and response decision
5.2.3	MoP	Time between response decision and order of response execution by decision-authorized entity
5.3.2	MoP	Median number of connections between decision-authorized entity and action-authorized entity
5.3.4	MoP	Percentage of entities connected by existing relationships and connections which are authorized to make a specific decision concerning a specific change in circumstances
5.4.1	MoP	Number of distinct response solutions generated by decision-authorized entities concerning a specific change in circumstances
5.5.2	MoP	Percentage of action-authorized entities with conflicting orders from decision-authorized entities
6.1.3.3	MoP	Percentage of action-authorized entities which are allocated a role or responsibility which they cannot accomplish
6.2.1	MoP	Time between order of response execution by decision-authorized entity and completion of allocations by allocation-authorized entity
6.2.2	MoP	Time between allocation of role or responsibility and commencement of role or responsibility by action-authorized entity
6.3.2	MoP	Median number of connections between allocation-authorized entity and action-authorized entity
6.3.4	MoP	Percentage of entities connected by existing relationships and connections which are authorized to make allocations concerning a specific decision
6.4.2	MoP	Percentage of roles and responsibilities which are required for the specific decision which are not allocated

Table 25. Selected Measures of Merit

APPENDIX E: FUNCTIONAL DECOMPOSITION

A function is a process that takes inputs and transforms them into outputs [Buede, 2000: 178]. Recall that a system is "a set of components (subsystems, segments) acting together to achieve a set of common objectives via the accomplishment of a set of tasks" [Buede, 2000: 38]. A system, therefore, is defined by 1) its set of objectives and 2) the functions required for it to achieve such set of objectives. As discussed in Appendix C: External Systems Diagram, the execution of the C2 process is the objective of a C2 system. The functional architecture describes how the system transforms the given inputs into the desired outputs.

This appendix will describe concepts pertinent to the functional decomposition of a naval tactical command and control system not previously described in the body of this thesis. The first section will discuss C2 functions identified by past researchers. The second section will present concepts concerning information and human decision making influential to the definition of functions and sub-functions.

A. SURVEY OF COMMAND AND CONTROL FUNCTIONS

As during the development of the operational concept, a publication review was conducted to provide the author with a foundational knowledge of the functions of command and control. Though by no means an exhaustive review, the author did seek to review many of most referenced contemporary publications. As stated above, the execution of the C2 process is the objective of a C2 system. Therefore, many of the publications reviewed contained conceptual models of the C2 process. Table 26. through Table 32. present functions of C2 systems and subsystems taken from these references.

Command and Control Functions			
Establish Intent	Define roles, responsibilities and relationships	Establish rules and constraints	Monitor and assess the situation and progress
Inspiring, motivating, and engendering trust	Training and education	Provisioning	

Table 26. Command and Control Functions [from Alberts & Hayes, 2006: 35-36]

Command and Control Functions				
Collecting Information	Storing Information	Retrieving Information	Filtering Information	Classifying Information
Distributing Information	Displaying Information	Form Estimate of Situation	Establish Objectives	Make Decision
Plan	Draft Orders	Transmit Orders	Execute Orders	Monitor Order Execution with Feedback

Table 27. Command and Control Functions [from Van Creveld, 1985: 6-7]

Command and Control Functions				
Sense	Process	Compare	Decide	Act

Table 28. Command and Control Functions [from Lawson, 1981]

Command and Control Functions					
Sense	Assess	Generate	Select	Plan	Act

Table 29. Command and Control Functions [after Levis & Athans, 1988]

Defensive Command and Control Functions			
Threat Detection	Target Tracking	Discrimination	Identification
Battle Planning	Weapon-to-Target Assignment	Engagement Control	Damage Assessment

Table 30. Defensive Command and Control Functions [from Athans, 1986: 6-7]

Target Engagement Functions					
Find	Fix	Track	Target	Engage	Assess

Table 31. Target Engagement Functions [from JP 3-60, 2007]

Communications Systems Functions			
Acquire Information	Store Information	Control other Communication Functions	Disseminate Information
Process Information	Transport Information	Protect Information	Present Information

Table 32. Communications Systems Functions [from JP 6-0, 2006: Ch I, 6-8]

B. INFORMATION AND HUMAN DECISION MAKING

The basic external systems diagram developed in the operational concept shows that *people* and the *communications & information systems* are two categories of components of the C2 system and that inputs to and outputs form the system, along with the cross-communication between the subsystems, is *information*. Understanding what humans and automated systems can bring to the C2 process can be beneficial in the decomposition of the top-level functions. Additionally, understanding the forms of information and the processes to convert one form of information into another can enlighten the system engineer to other potential sub-functions of the C2 system.

1. Cognitive Hierarchy

Information comes in many forms. One form of information is transformed to another form of information through a process. Ackoff [1989] posits that the forms of information are actually structured in a hierarchy of five forms. The lowest form of information in his hierarchy is data, which he contends is a product of observation. Information, the next highest form of information in his hierarchy, is data which has been "processed into a useable (i.e., relevant) form" [Ackoff, 1989: 3]. Learning, either by instruction or by extracting it from experience, transforms information into knowledge [Ackoff, 1989: 4]. Ackoff describes learning with changing conditions as adaption. He then contends that systematic learning and adaption, through diagnosis and prescription, transforms knowledge into understanding. Finally, wisdom is understanding with value, judgment being the mental function which transforms understanding into wisdom. Ackoff's hierarchy of information and processes is presented in Figure 46.

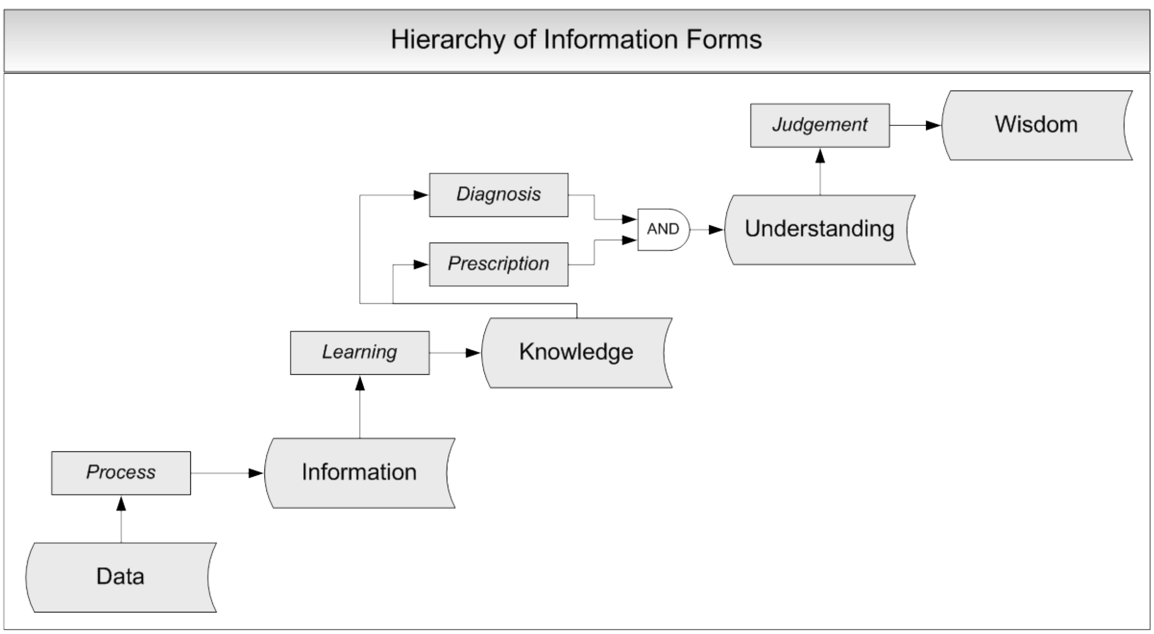

Figure 46. Hierarchy of Information Forms [after Ackoff, 1989]

There are many concepts within Ackoff's hierarchy which have significant pertinence to this thesis. First, the most obvious given the explanation above, is that information comes in many forms. Second, non-human systems can be built that perform all of the processes except judgment, which is solely a capability of humans. This differs

significantly from similar hierarchies described in Naval Doctrine Publication 6 [1995: 21] and Marine Corps Doctrine Publication 6 [1996: 67] that contend knowledge and above requires cognition, a human-only capability. Figure 47. and Figure 48. present each, respectively. The third significant idea which is inferred from Ackoff's hierarchy is that, just as there is a process to convert one form to a higher form, there must be a process to convert one form to a lower form. This is best understood with the fourth significant idea, also inferred, that transmission of a form of information requires that it be transformed into data.

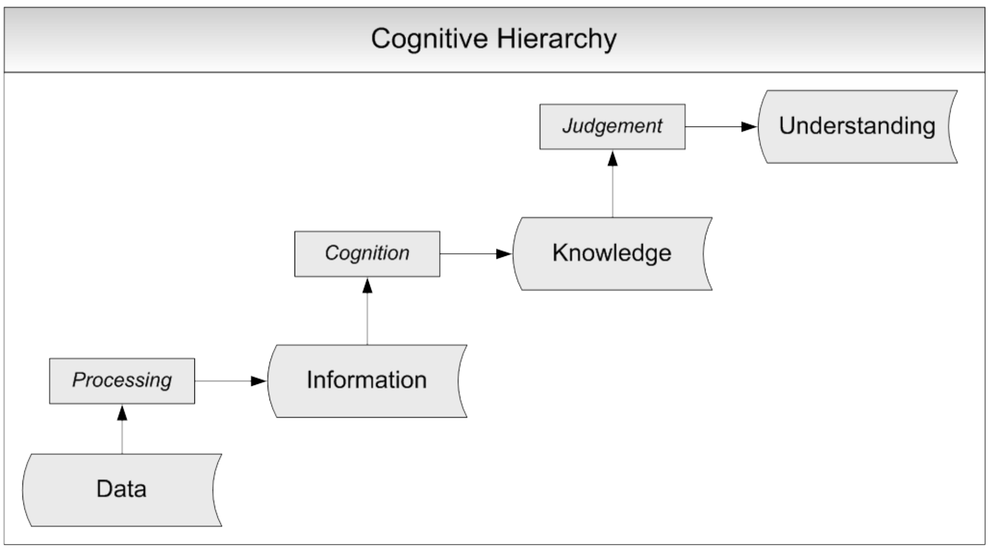

Figure 47. Cognitive Hierarchy [after NDP 6, 1995: 21]

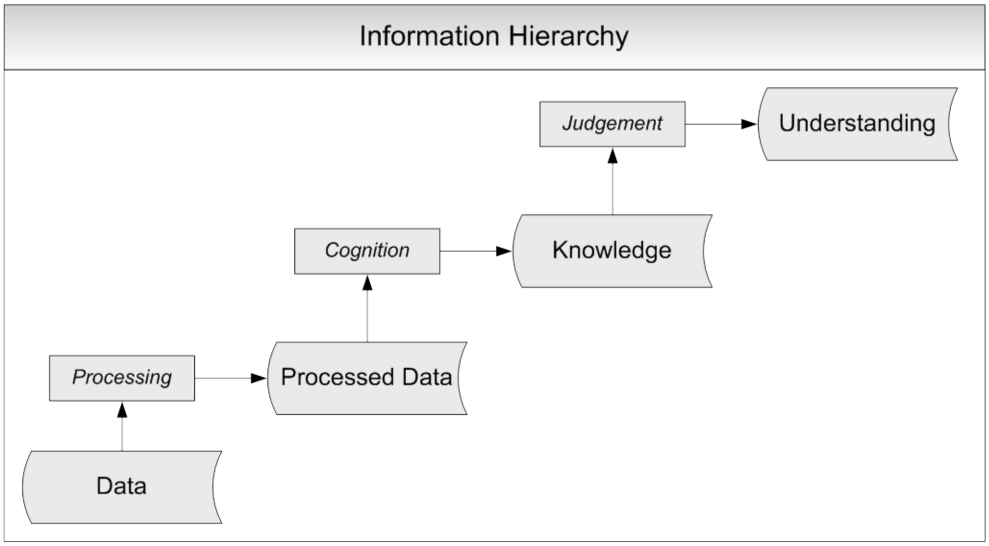

Figure 48. Information Hierarchy [after MCDP 6, 1996: 67]

To understand the third and fourth ideas, take the example where one person has a piece of knowledge which they wish to share with another person. As Ackoff explains, this is done through instruction [pg. 4]. To gain knowledge, the student has to learn information. To learn the information, though, requires the student to observe the instruction by the instructor. The instructor, therefore, must transform his knowledge into data for the student to learn.

Communication of information, in whatever form, is based on the exchange of data through observation. Examples are numerous in human-to-machine communication (e.g., keyboards), machine-to-human communication (e.g., visual displays), and machine-to-machine communications (e.g., common protocols). A C2 system interfaces with external systems. Therefore, it must be capable of transforming its inputs, which are in the form of data, into useful information. It must also be capable of transforming its useful information into data to become output. *Process*, and its inverse function, must be a function of the C2 system. *Learning*, *diagnose*, *prescribe*, and their inverse functions are candidate functions as well. *Judgment* and its inverse are also candidate functions, but, as Ackoff contends, can only be executed by human components of the C2 system.

2. Human Decision Making

People and *communications & information systems* are two types of components of a C2 system. The significance of these two categories is that they highlight the types of entities within the system which can fill, partially or wholly, the functions of the C2 system – humans and automated systems. Understanding what humans and automated systems can bring to the C2 process can be beneficial in the decomposition of the top-level functions. The first step, then, is to review the process by which humans make decisions. Also, given that the commander is an external system, this review can identify inputs for the commander which may subsequently be outputs from the C2 system.

Human decision making is a major reason why command and control has been an enigma. Understanding and modeling human decision making has plagued engineers and analysts for as long as they have studied command and control. Many have developed conceptual models to explain all or part of the process. Despite the mystery of human decision making, reviewing several of these conceptual models of the process can enlighten the system engineer to potential sub-functions of *generate response options* and other top-level functions. The first conceptual model to review, which is perhaps the most famous amongst military scholars, is the Observation-Orientation-Decision-Action (OODA) Loop presented by Boyd [1996]. A depiction of the OODA Loop from Boyd's unpublished lecture notes is presented in Figure 49.

Boyd's OODA Loop is the culmination of decades of research and analysis which began with his study of air attack, then air-to-air combat, then finally to a more general theory of competition. The OODA Loop has been applied by contemporary scholars to describe the C2 process for groups, but Boyd's original intentions leading to the OODA loop was to describe the process an individual uses when combating another individual. It is from this individual, human decision making view that the OODA loop will be used for generating sub-functions. Boyd did not formally publish any of his work, choosing rather to give lectures concerning his concepts, and unfortunately the author was not able to attend any of his lectures. Therefore, the discussion below is a result of the author's review of Boyd's unpublished lecture notes.

The OODA Loop is a relatively straightforward conceptual model with nearly the entire concept neatly depicted in Figure 49. Competition for an individual is an iterative process of four phases – *observation, orientation, decision, and action*. Each phase feeds forward to the next phase and each phase provides feedback to *observation*. There are six inputs to the process, or in other words six inputs to the human decision making system. Three of the inputs are within *observation* (outside information, unfolding circumstances, and unfolding environmental interaction) and three within *orientation* (cultural traditions, genetic heritage, and previous experiences; new information is product of *observation*). These six inputs are analyzed and synthesized during orientation to feed the *decision* and *action* phases. The analysis and synthesis of the inputs, as Boyd contends, is the most crucial to the entire decision making process.

> The second O, orientation – as the repository of our genetic heritage, cultural tradition, and previous experiences – is the most important part of the O-O-D-A loop since it shapes the way we observe, the way we decide, and the way we act. [Boyd, 1987: 26]

From this basic review of the OODA Loop, the system engineer can conclude that the human decision making system is comprised of six top-level functions – observe, orient, hypothesize, test, decide, and act. In addition, the sub-functions of orient are analyze and synthesize.

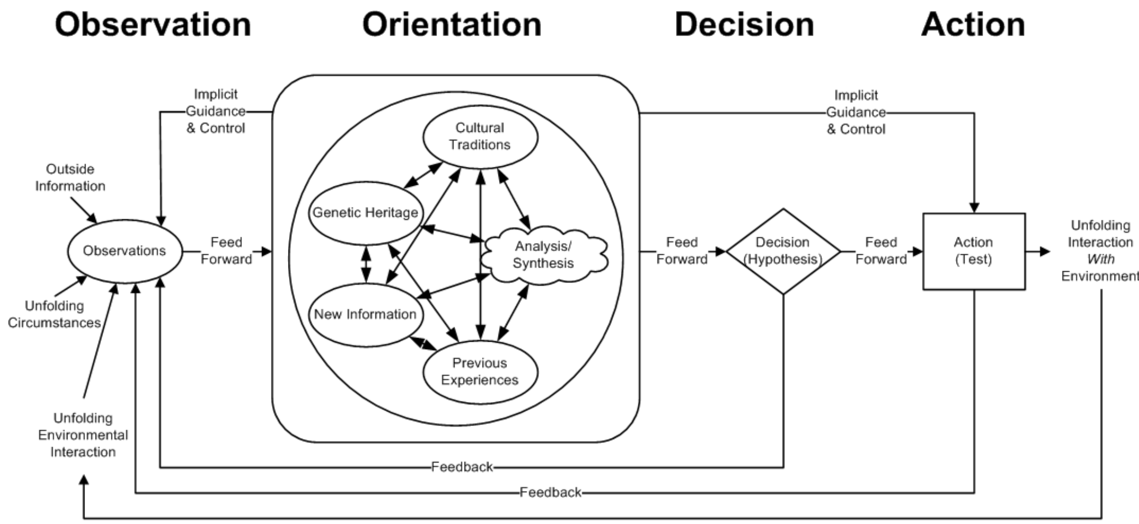

Figure 49. OODA Loop [from Boyd, 1996]

The second conceptual model to review is the Recognition-Primed Decision Making (RPD) model presented by Klein [1988]. Klein contends that there are two types of approaches to decision making, one analytical and the other recognitional. Analytical approaches, Klein argues, are most appropriate in situations with “low time pressure, need for careful documentation, and context free task with many components” while recognitional approaches are appropriate in situations with “high time pressure, highly experienced decision maker, low need for precision, and strong contextual influences” [1988, 86]. From previous work with other researchers, Klein presents and discuses the RPD model developed, which is shown in Figure 50.

In the simplest case of the RPD model, the decision maker uses cues of the situation and knowledge to recognize a situation. The recognition also incorporates the goals which “can be achieved, what cues to monitor, and other types of expectancies” [Klein, 1988: 87]. From this recognition, the decision maker identifies the typical response and implements the action. In the next case, when time is available, the decision maker evaluates the typical action and implements the action. No other actions other than the typical action are considered or evaluated. In the final case of RPD, again when time is available, the decision maker evaluates the typical reaction from a queue of actions. The action may be implemented, modified, or rejected. If the action is rejected, another action from the queue is evaluated and then implemented, modified, or rejected.

This process continues until an action is selected and implemented. A difference between recognitional and analytical approaches is that, for example, in the final case of RPD the actions are evaluated in series and are not compared with each other.

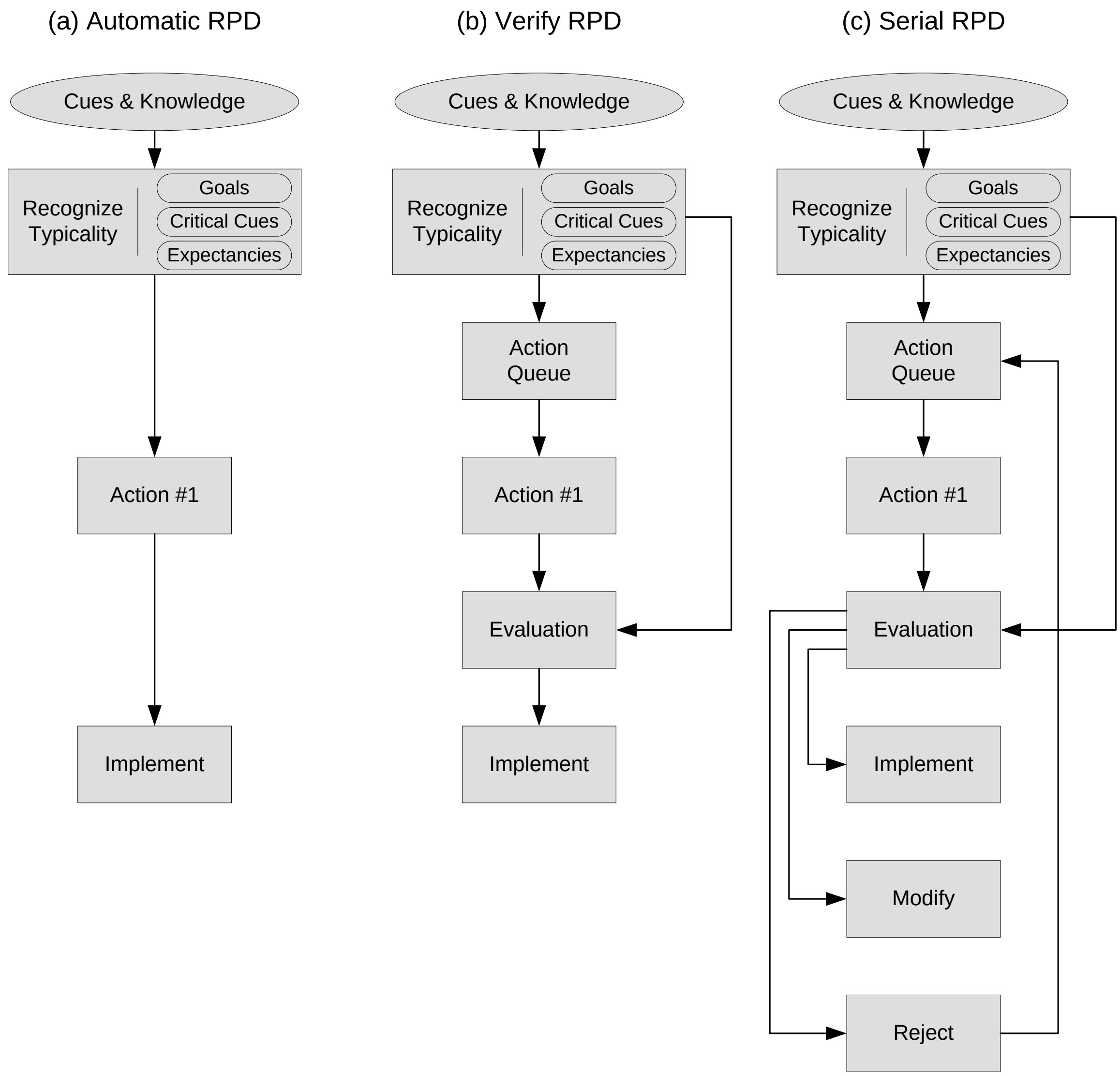

Figure 50. Recognition-Primed Decision Making [from Klein, 1988]

Though both conceptual models have yielded relatively few ideas for sub-functions of the C2 system, they have identified system outputs and possible constraints to the outputs. A C2 system's outputs to the decision making person, when one exists, include information concerning the environment, the interaction between the force and the environment, and any other outside information pertinent to the environment (e.g.,

updated ROE). Constraints on the C2 system may be to present the outputs to the decision maker taking into account inputs outside of the C2 system, namely genetic heritage, cultural traditions, and previous experiences. In addition, when time is critical, it may be best for the C2 system to present response options in series rather than in a set.

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APPENDIX F: INPUT-OUTPUT RELATIONSHIPS

After the functional hierarchy was detailed, the next phase of the functional architecture development was to describe the relationships between inputs and outputs of the system. During the operational concept, interaction diagrams were developed demonstrating the relationship between certain inputs, outputs, and the system. This appendix presents the further detail to explain the process (i.e., sequence of functions) by which inputs are converted into outputs.

Below is a collection of relationship diagrams developed for this thesis using IDEF0. The color selection of lines and font are not standard for IDEF0 but were implemented to make the relationship diagrams more easily readable. Red lines and red, italic, sans-serif fonts denote procedures and controls, which will be discussed in the physical architecture. Blue lines and blue, bold, serif fonts denote mechanisms, again which will be discussed in the physical architecture. Black lines and black, sans serif fonts denote inputs and outputs. In those instances where an output of one function was a control for another function, the line and font was drawn in red.

The sub-diagrams presented below denote mechanisms which correspond to generic physical components which were developed in the physical architecture. Specific mechanisms, or instantiated physical components, for each function were identified and finalized during the development of the operational architecture. Further discussion of the mechanism, shown in the following figures, is presented in the physical architecture and operational architecture discussions.

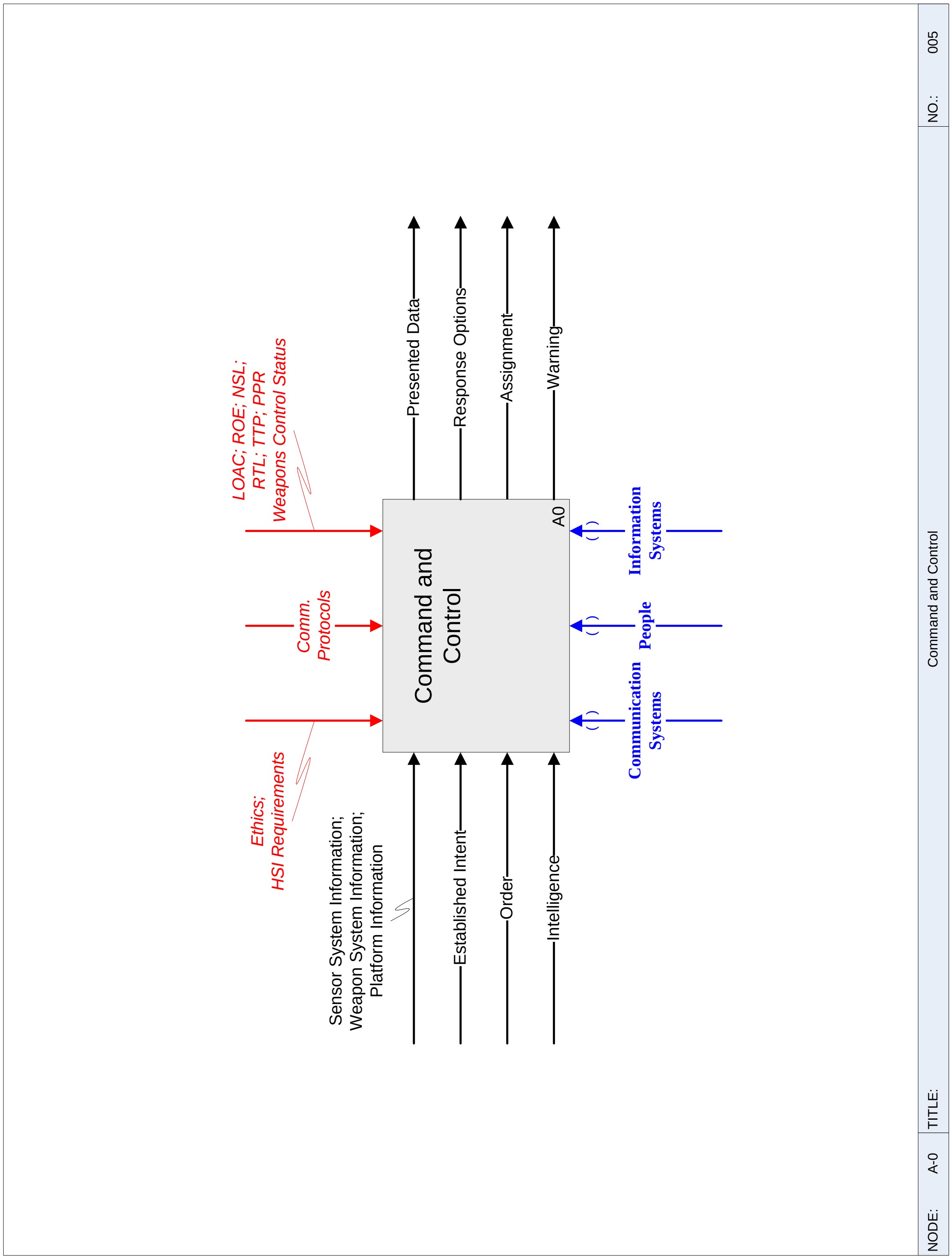

Figure 51. Relationship Diagram – A-0

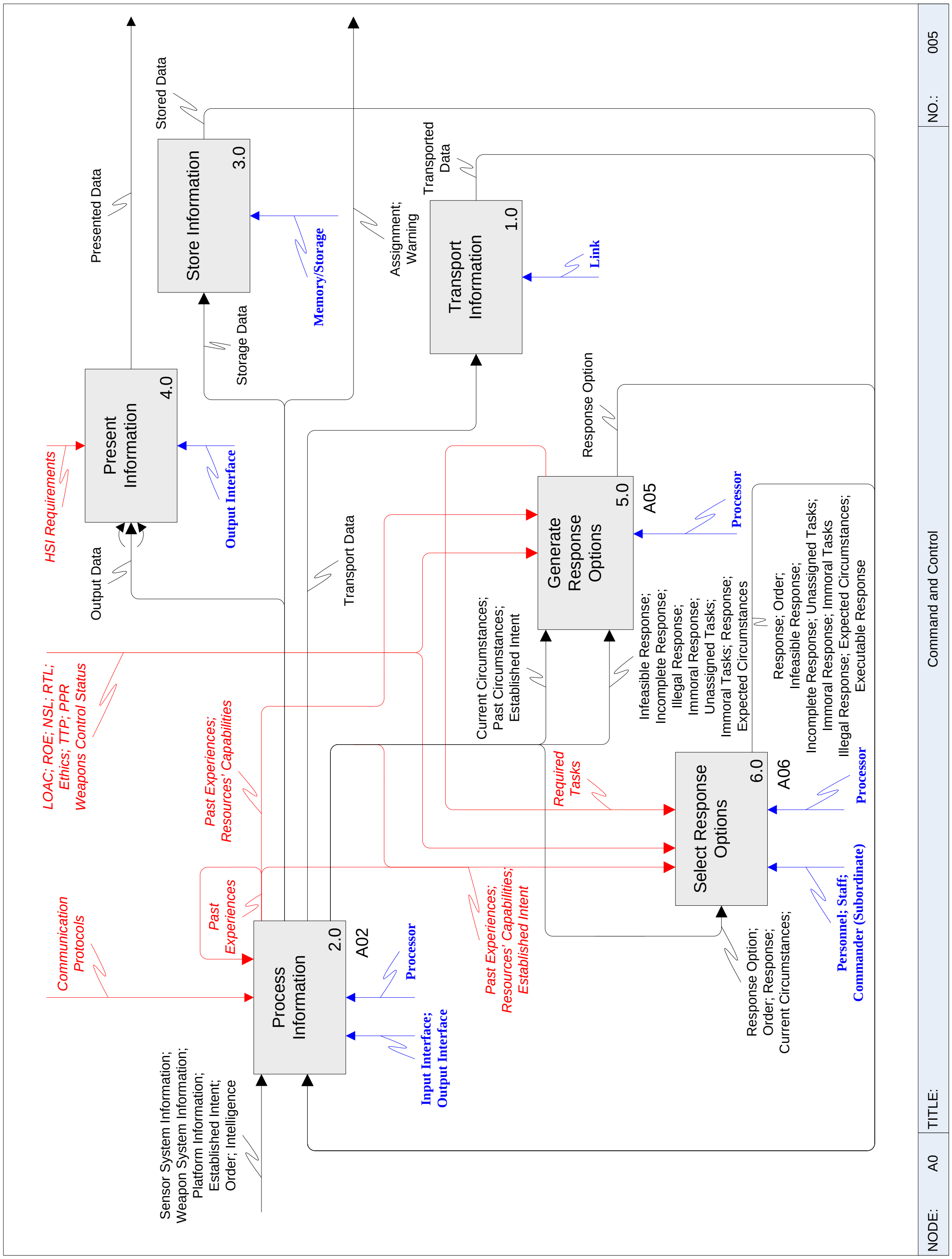

Figure 52. Relationship Diagram – A0

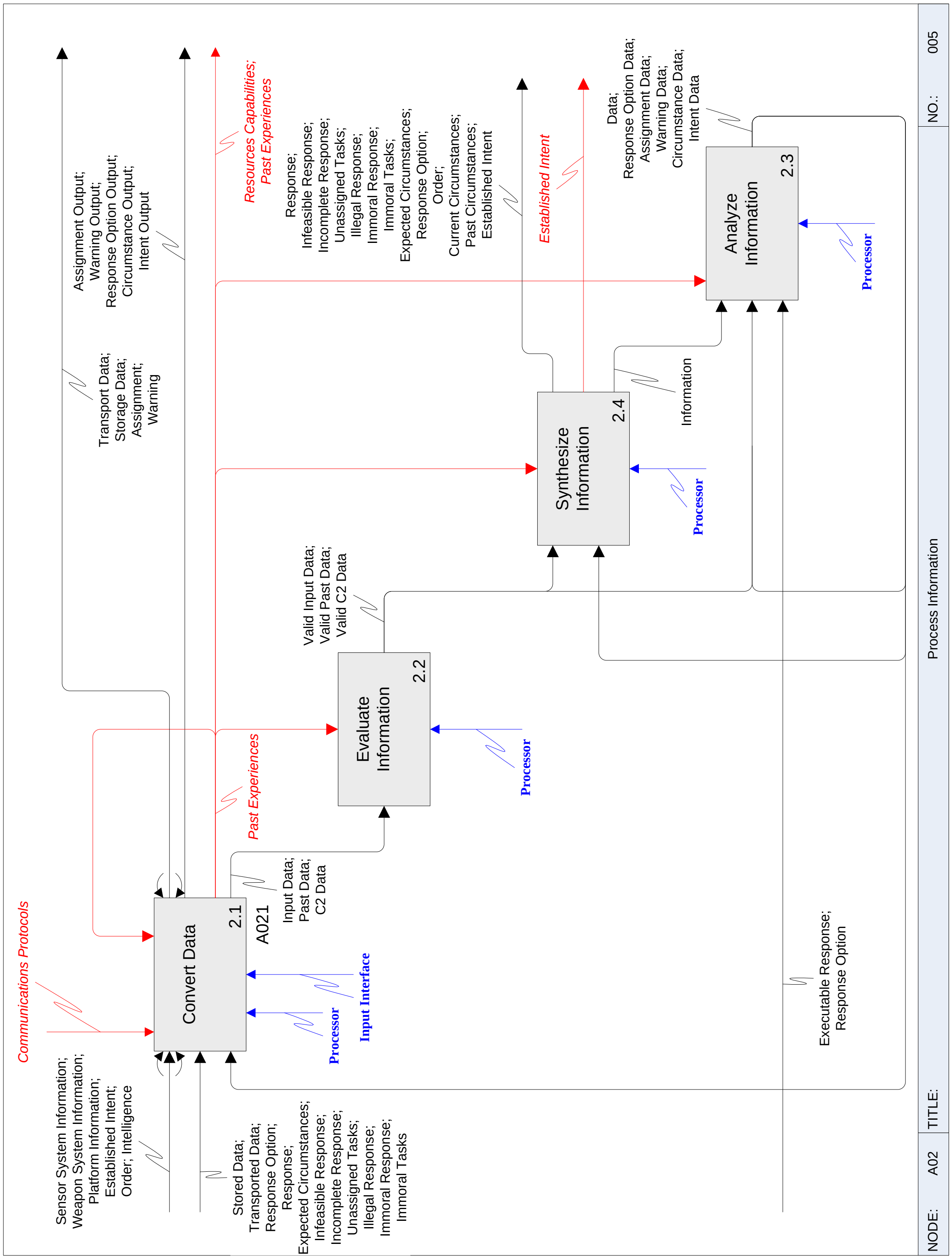

Figure 53. Relationship Diagram – A02

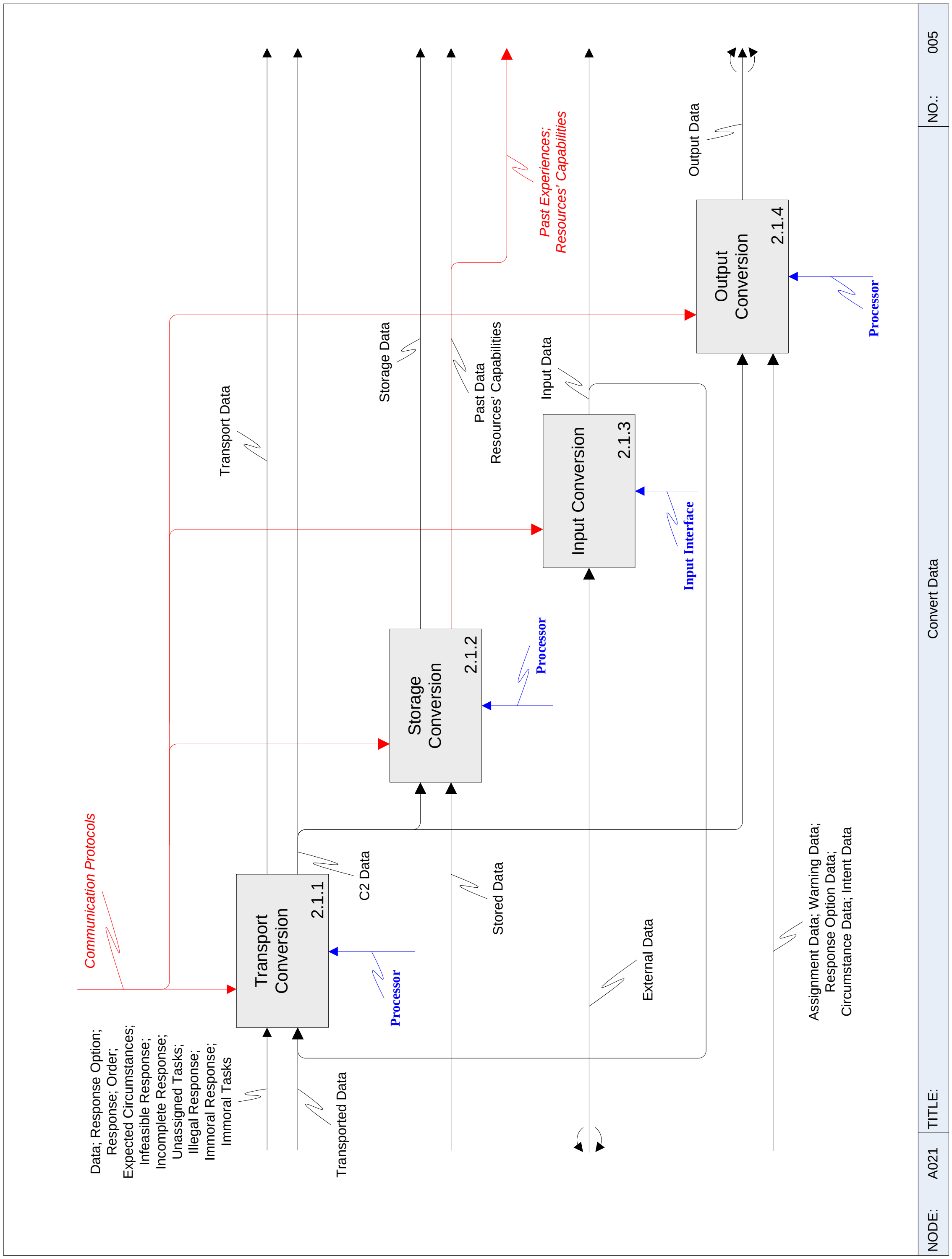

Figure 54. Relationship Diagram – A021

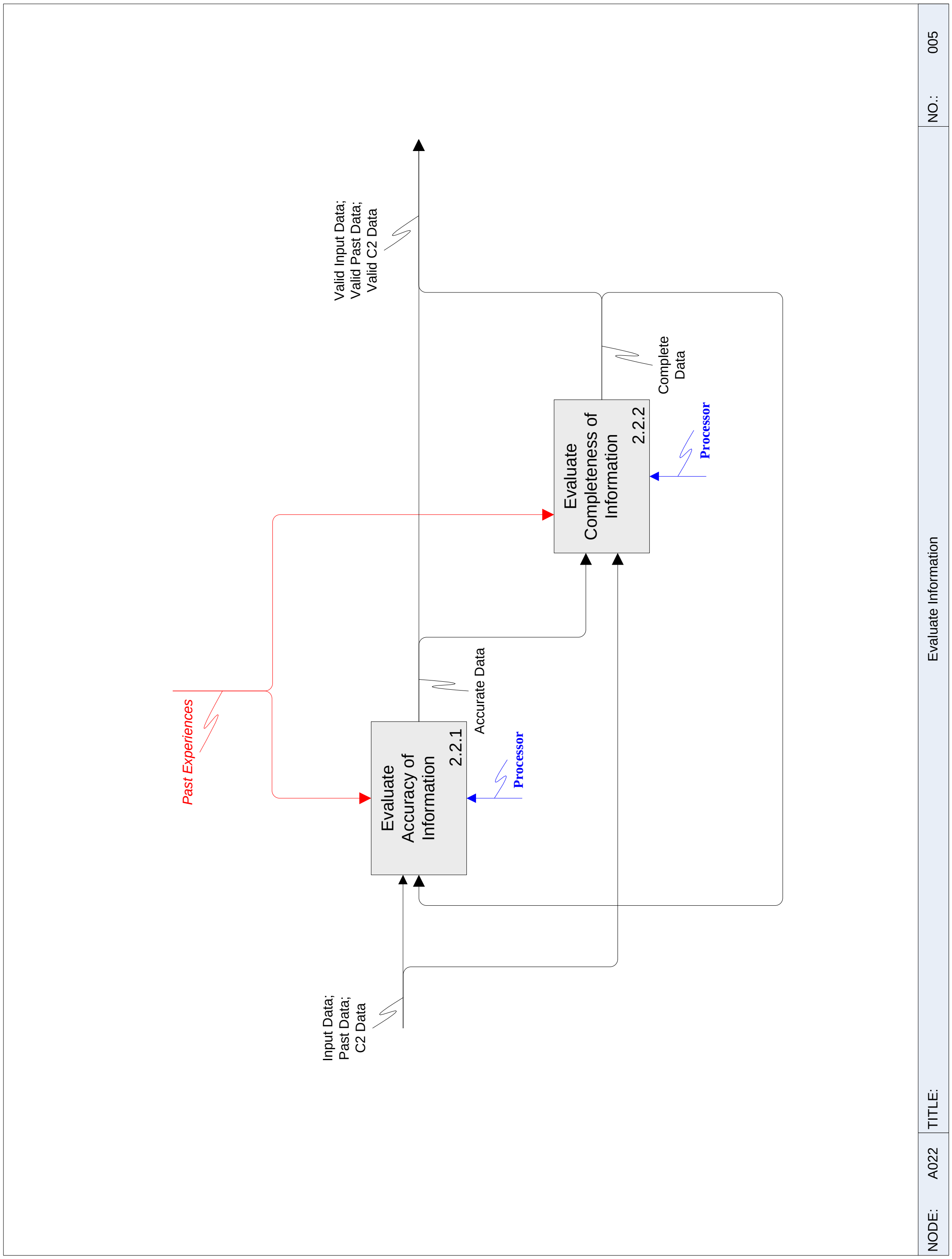

Figure 55. Relationship Diagram – A022

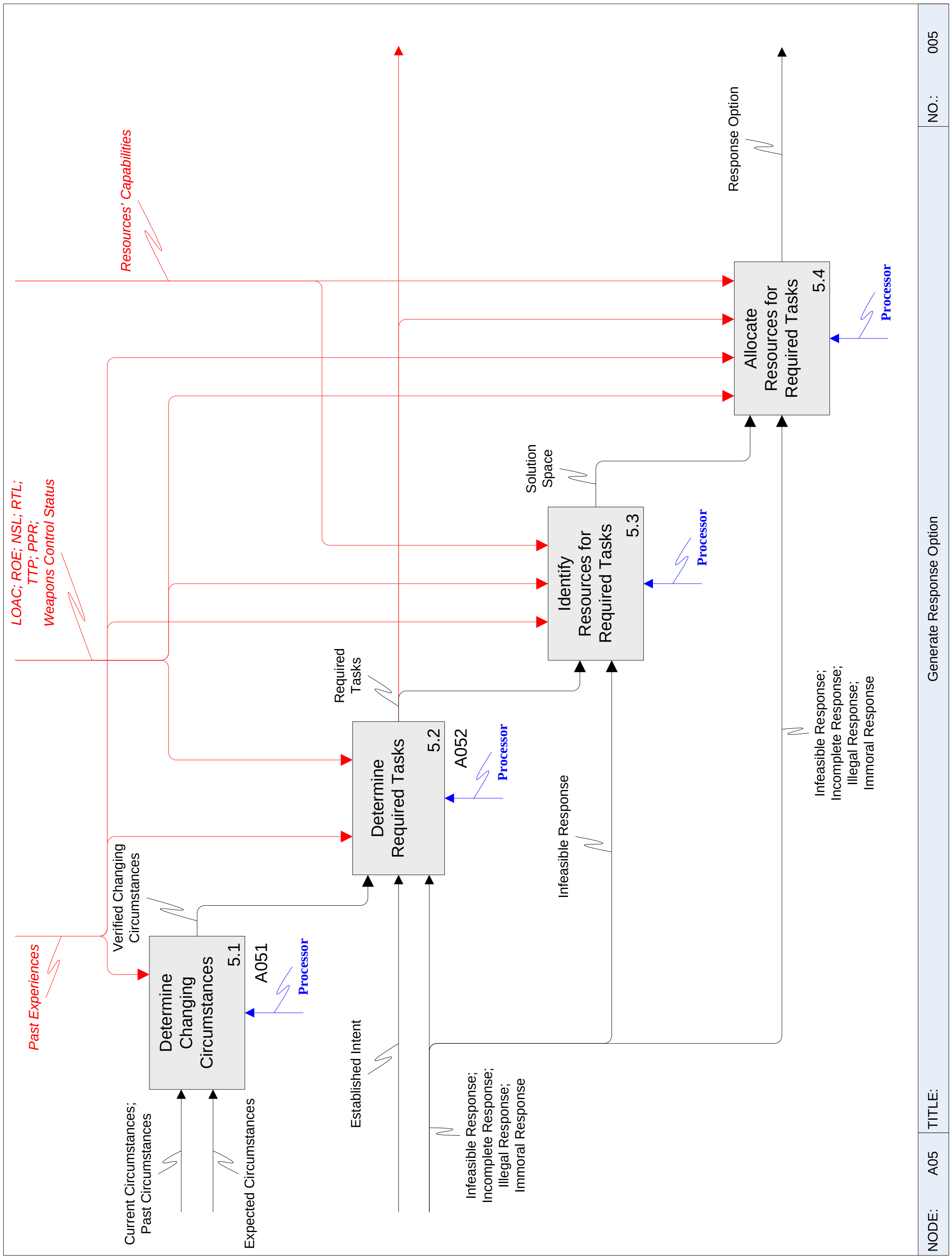

Figure 56. Relationship Diagram – A05

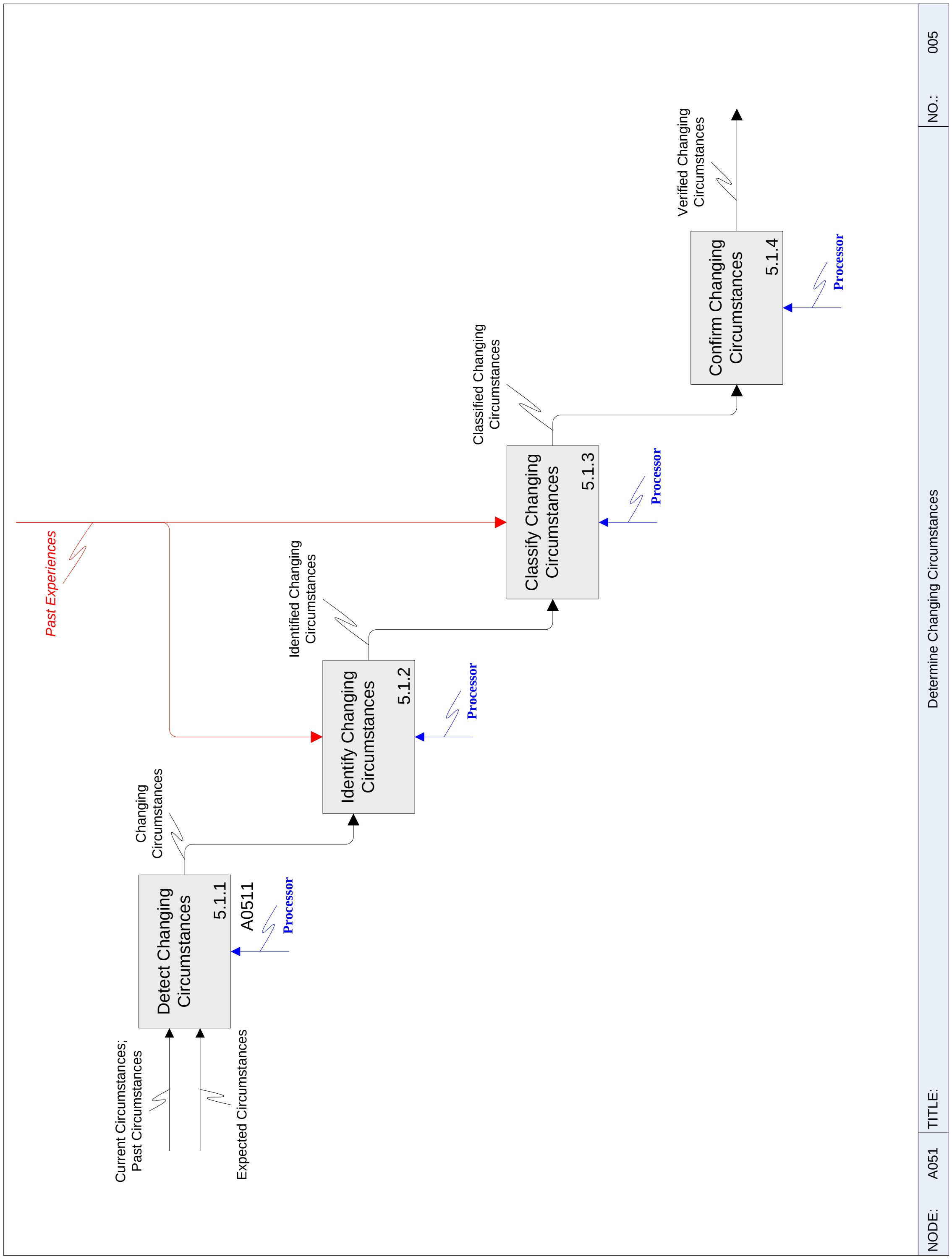

Figure 57. Relationship Diagram – A051

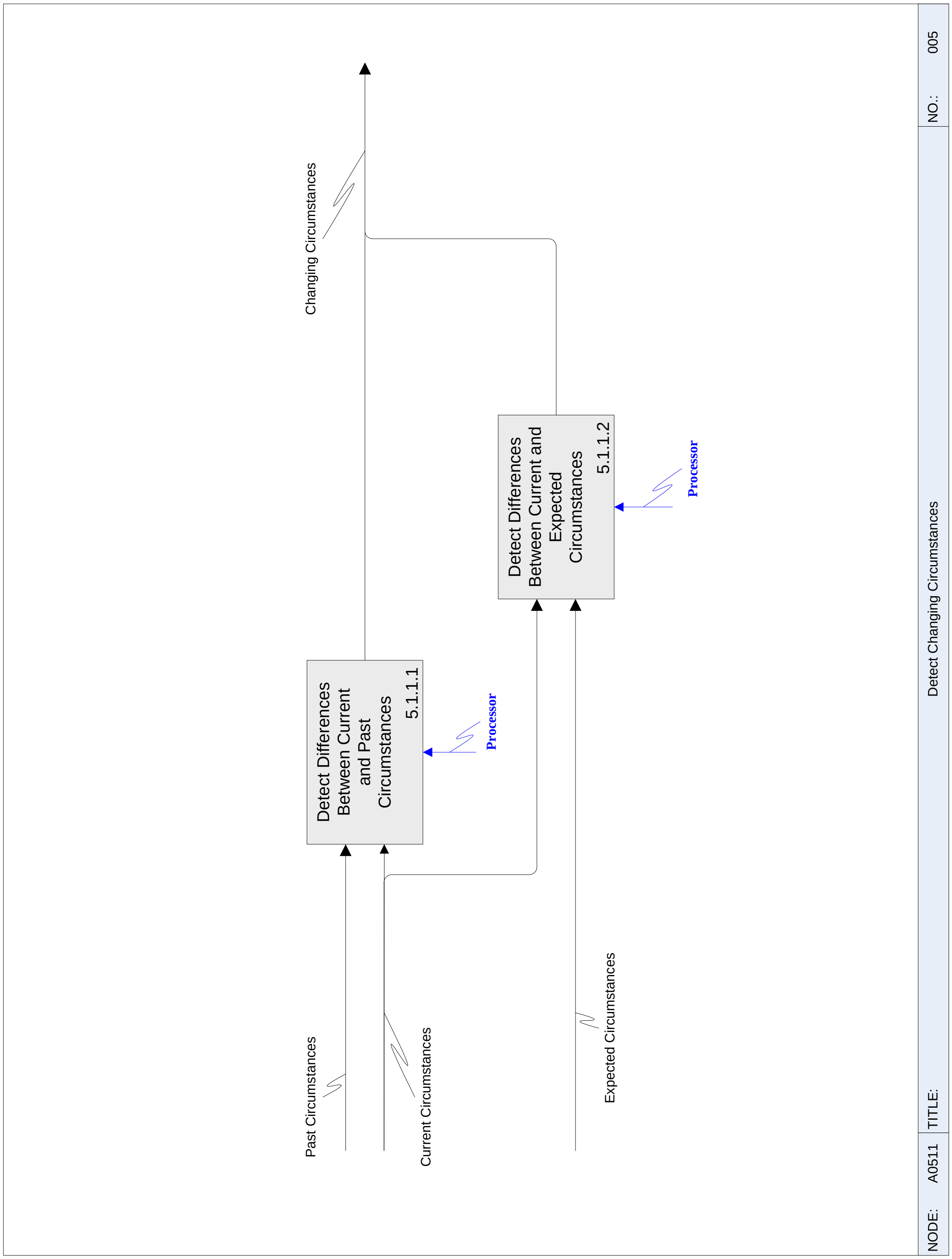

Figure 58. Relationship Diagram – A0511

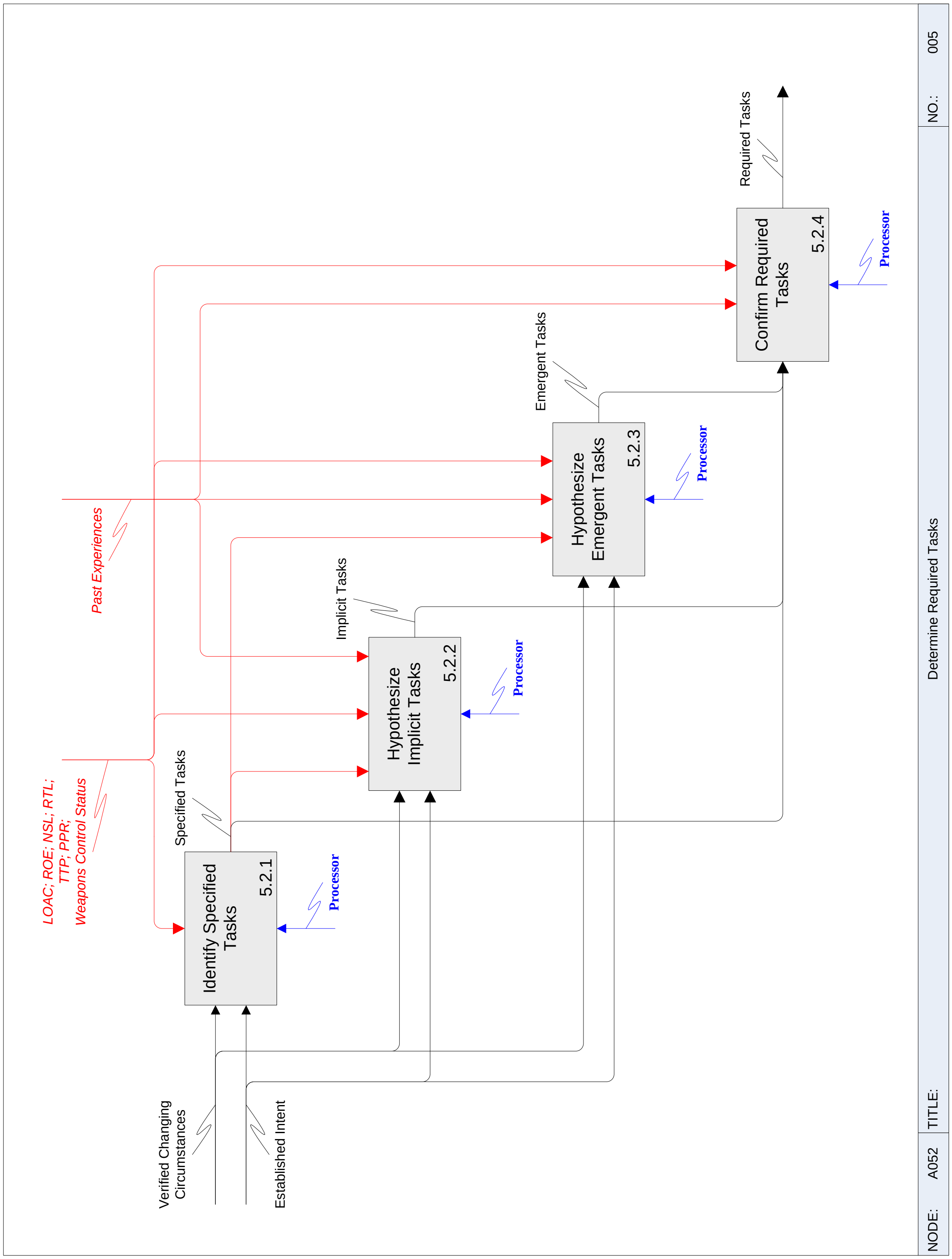

Figure 59. Relationship Diagram – A052

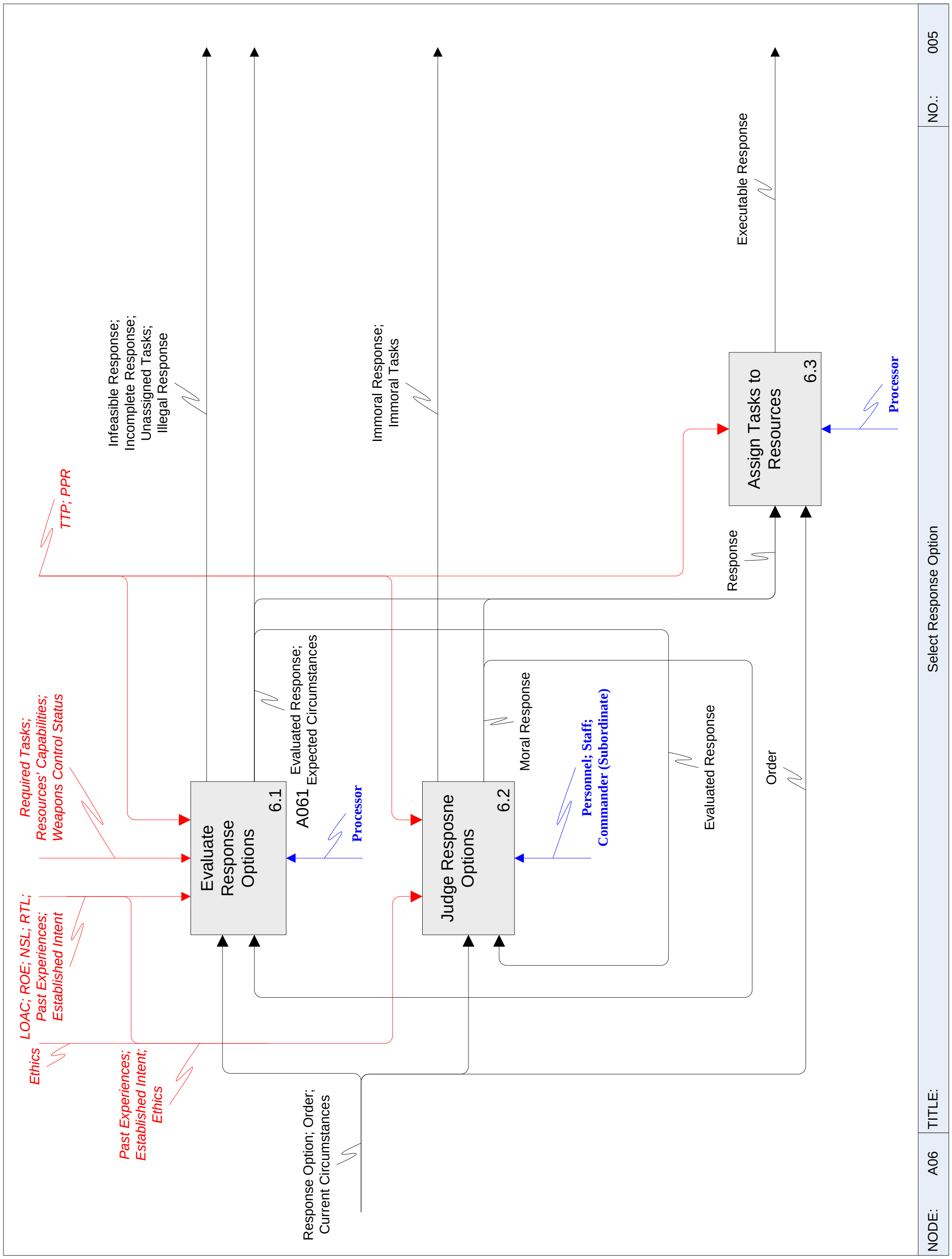

Figure 60. Relationship Diagram – A06

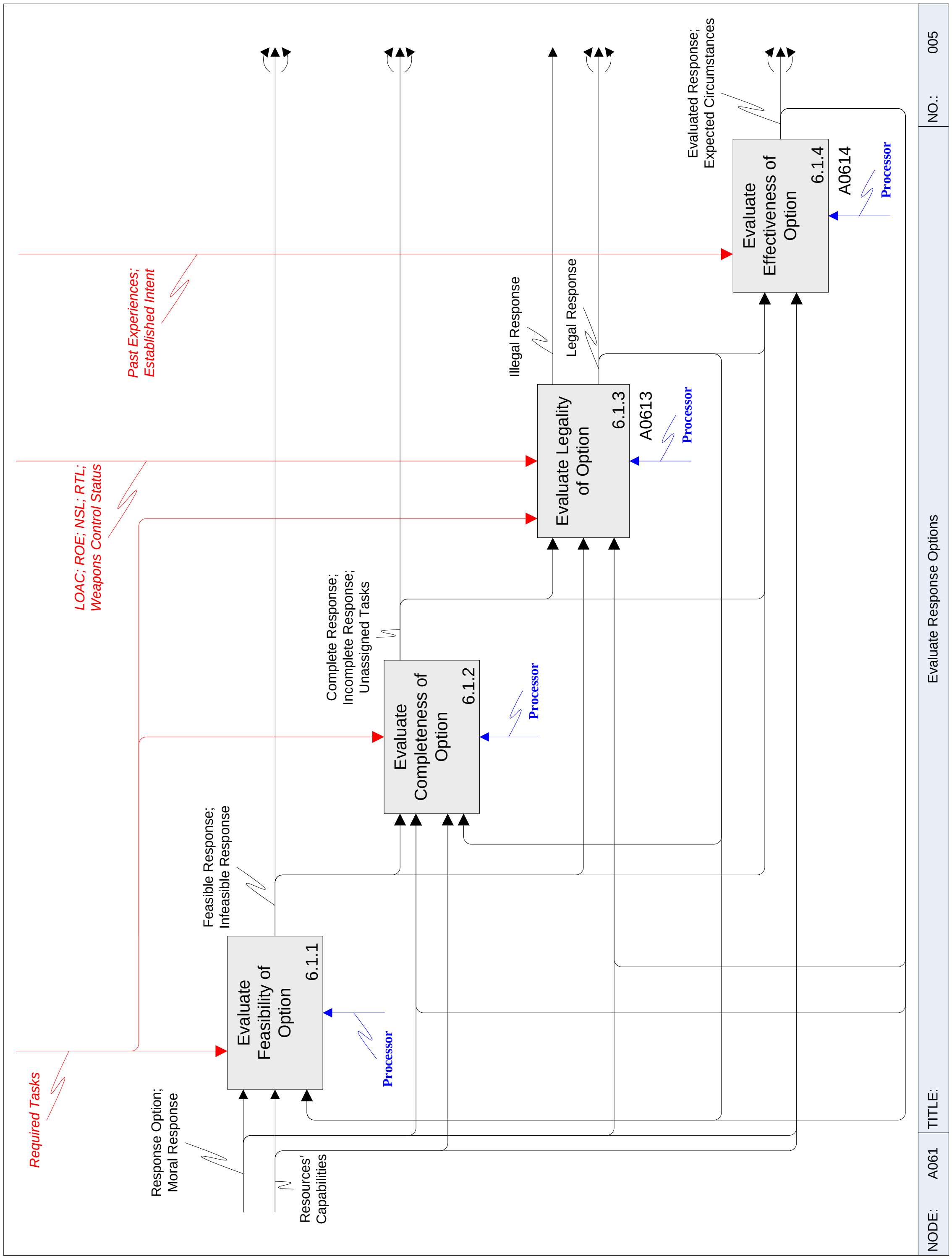

Figure 61. Relationship Diagram – A061

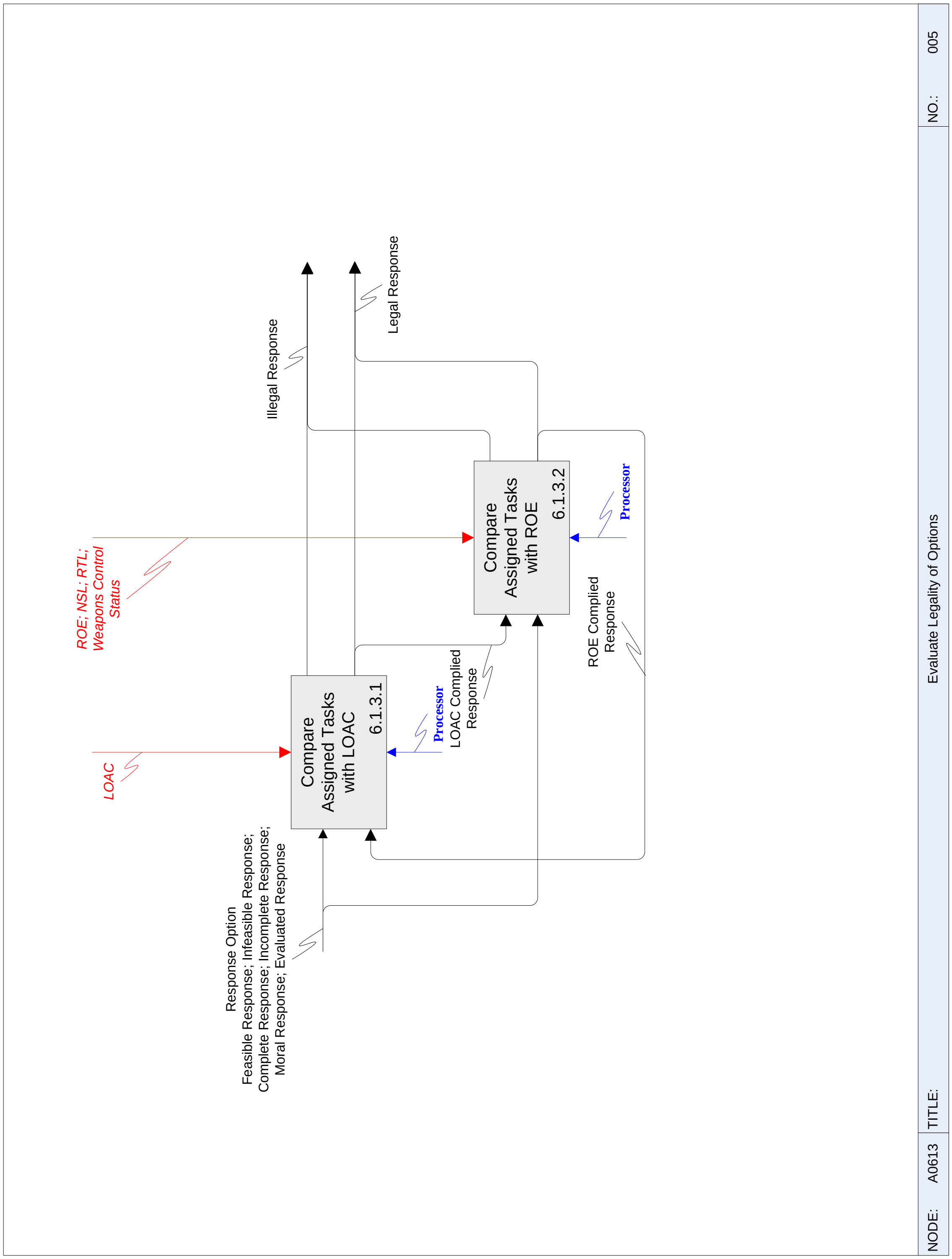

Figure 62. Relationship Diagram – A0613

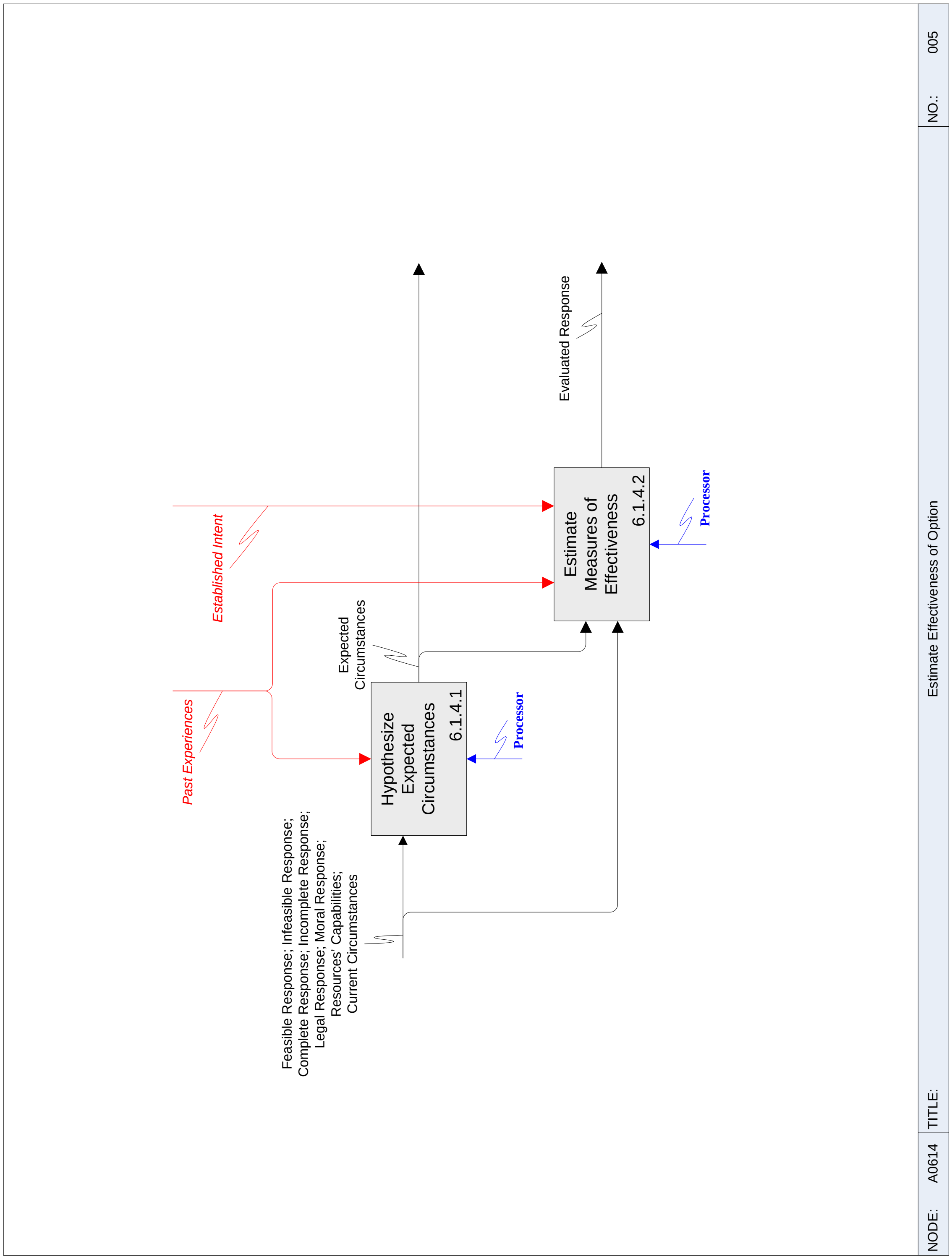

Figure 63. Relationship Diagram – A0614

APPENDIX G: OPERATIONAL ARCHITECTURE

The operational architecture provides a description of the system design, incorporating the products of the operational concept, functional architecture, and physical architecture. This appendix provides further documentation concerning the operational architecture to include the full collection of relationship diagrams developed modeling the contact prosecution process and the associated activation and controls of the functions. In addition, this appendix provides further detail of the Arena® model of the contact prosecution and the results of the simulations conducted.

A. CONTACT PROSECUTION

This section presents the key thread of processes converting inputs into outputs for contact prosecution. First, the collection of relationship diagrams using the IDEF0 methodology is presented. Second, the activation and controls of the pertinent functions in the contact prosecution process is presented.

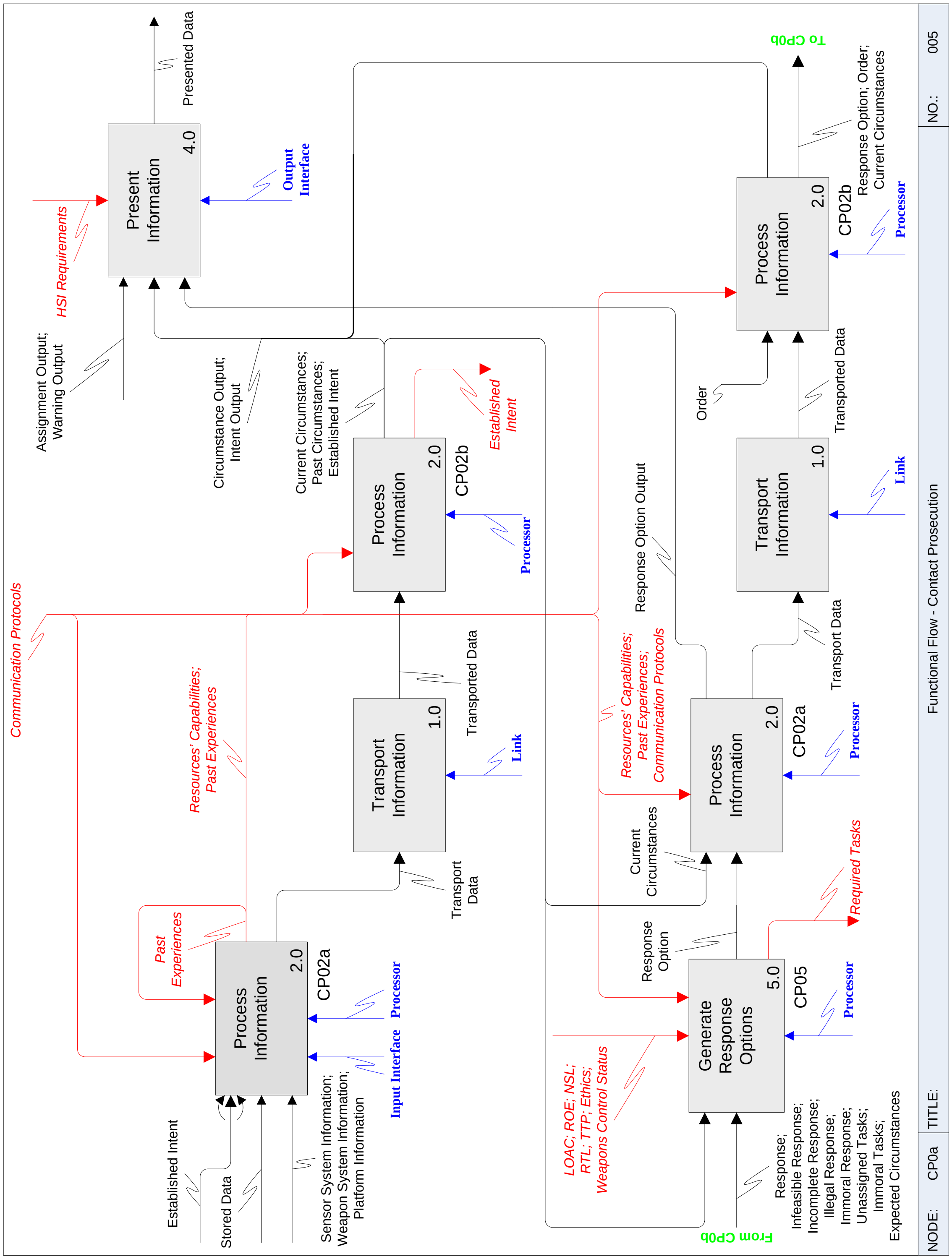

Figure 64. Relationship Diagram - CP0a

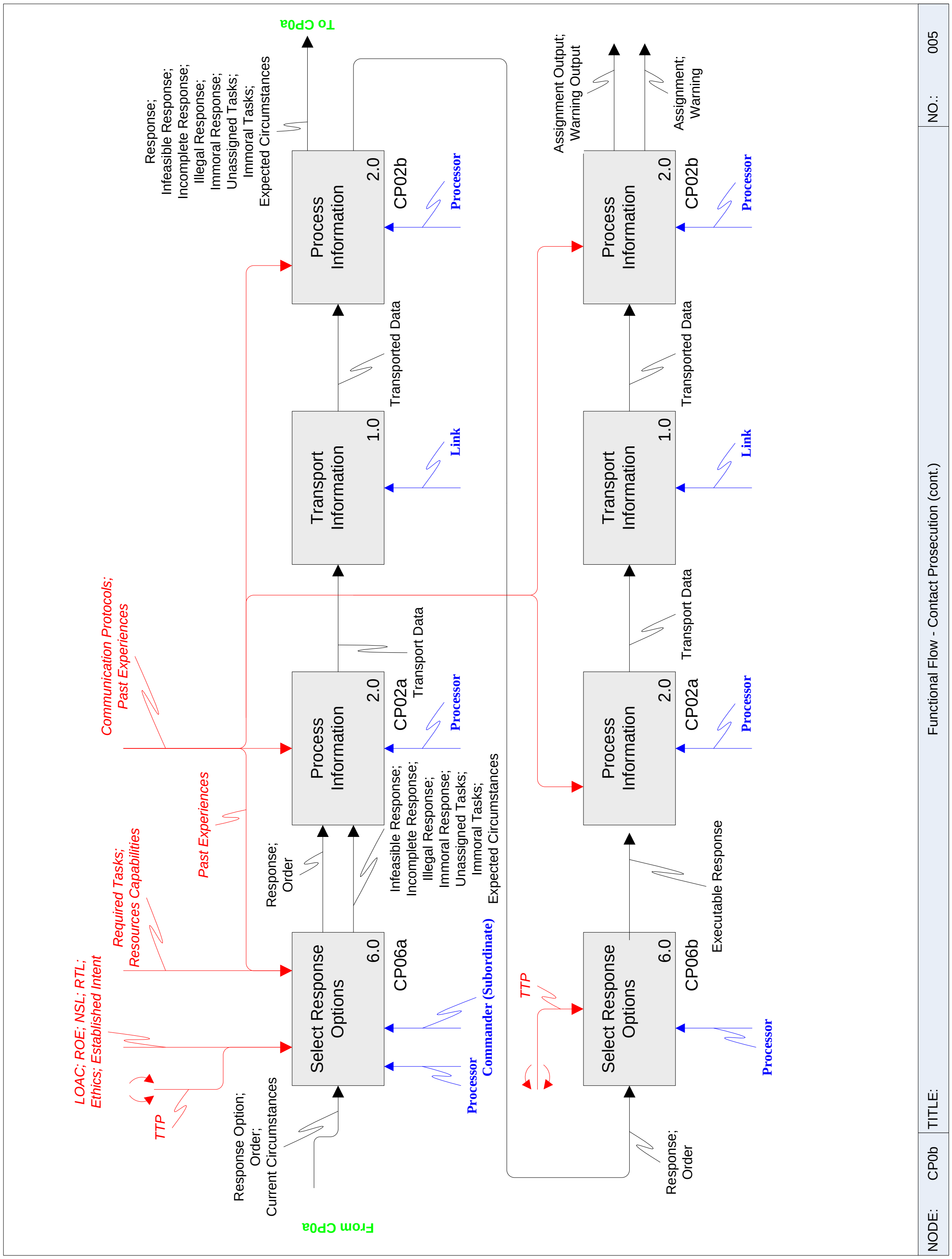

Figure 65. Relationship Diagram - CP0b

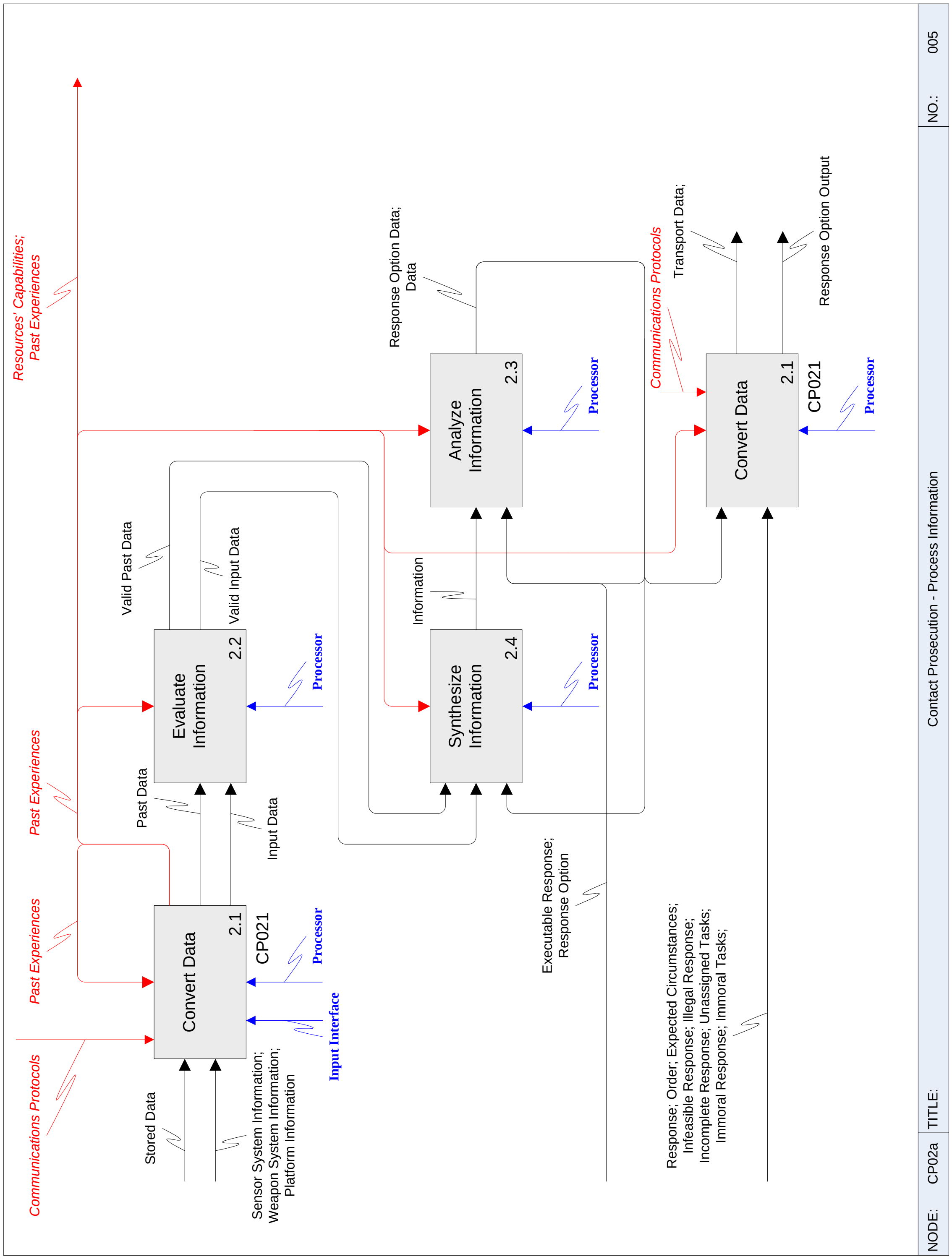

Figure 66. Relationship Diagram – CP02a

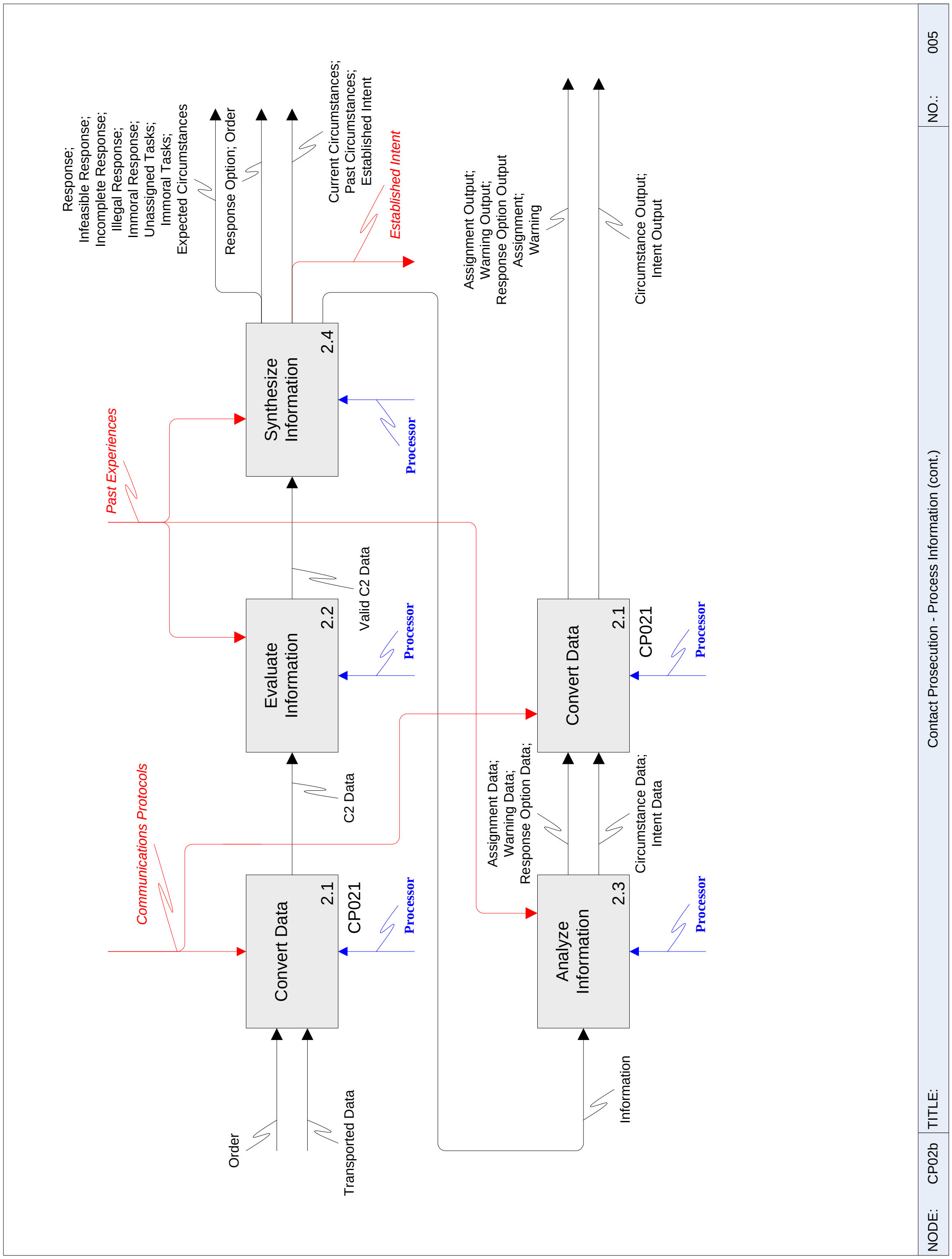

Figure 67. Relationship Diagram – CP02b

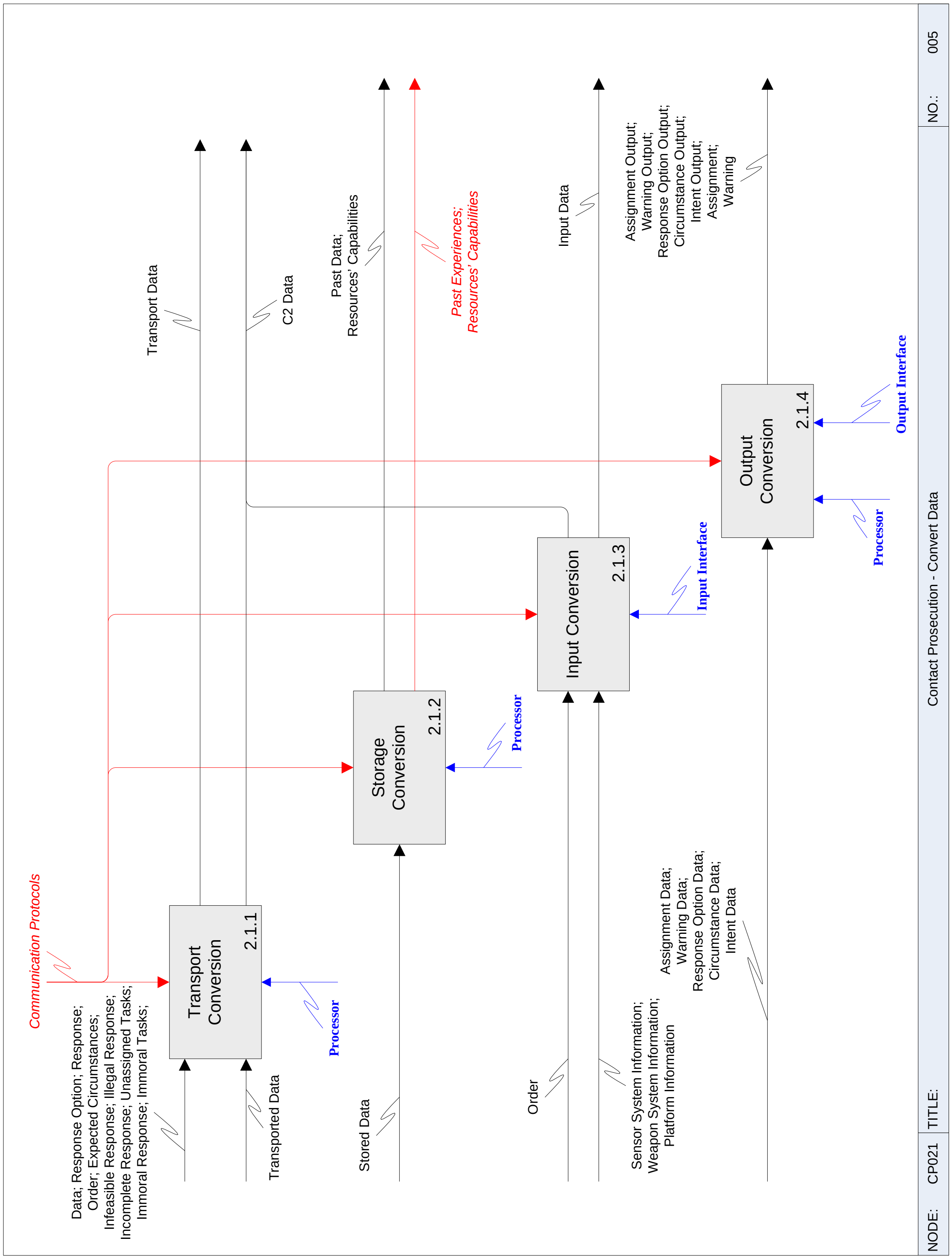

Figure 68. Relationship Diagram – CP021

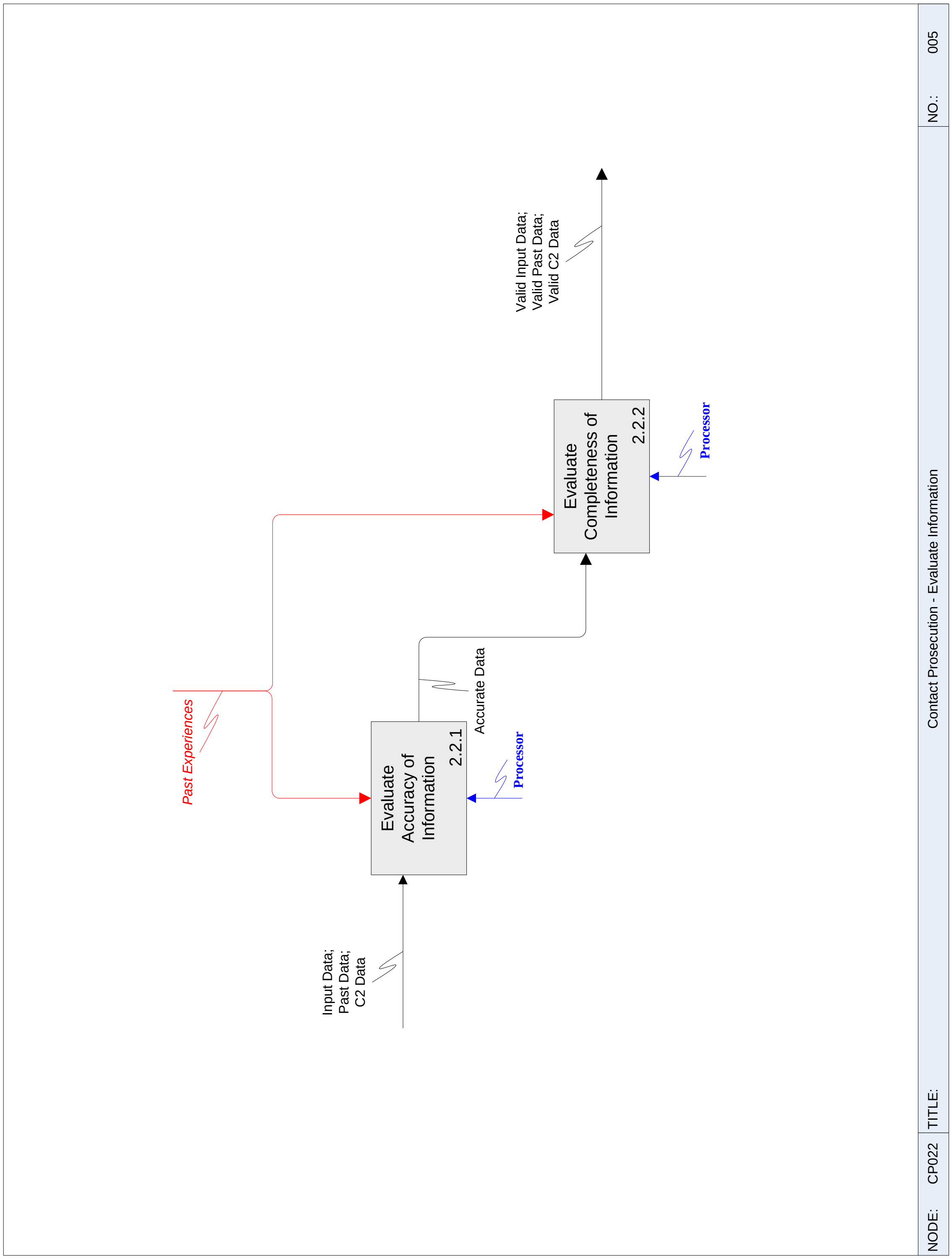

Figure 69. Relationship Diagram – CP022

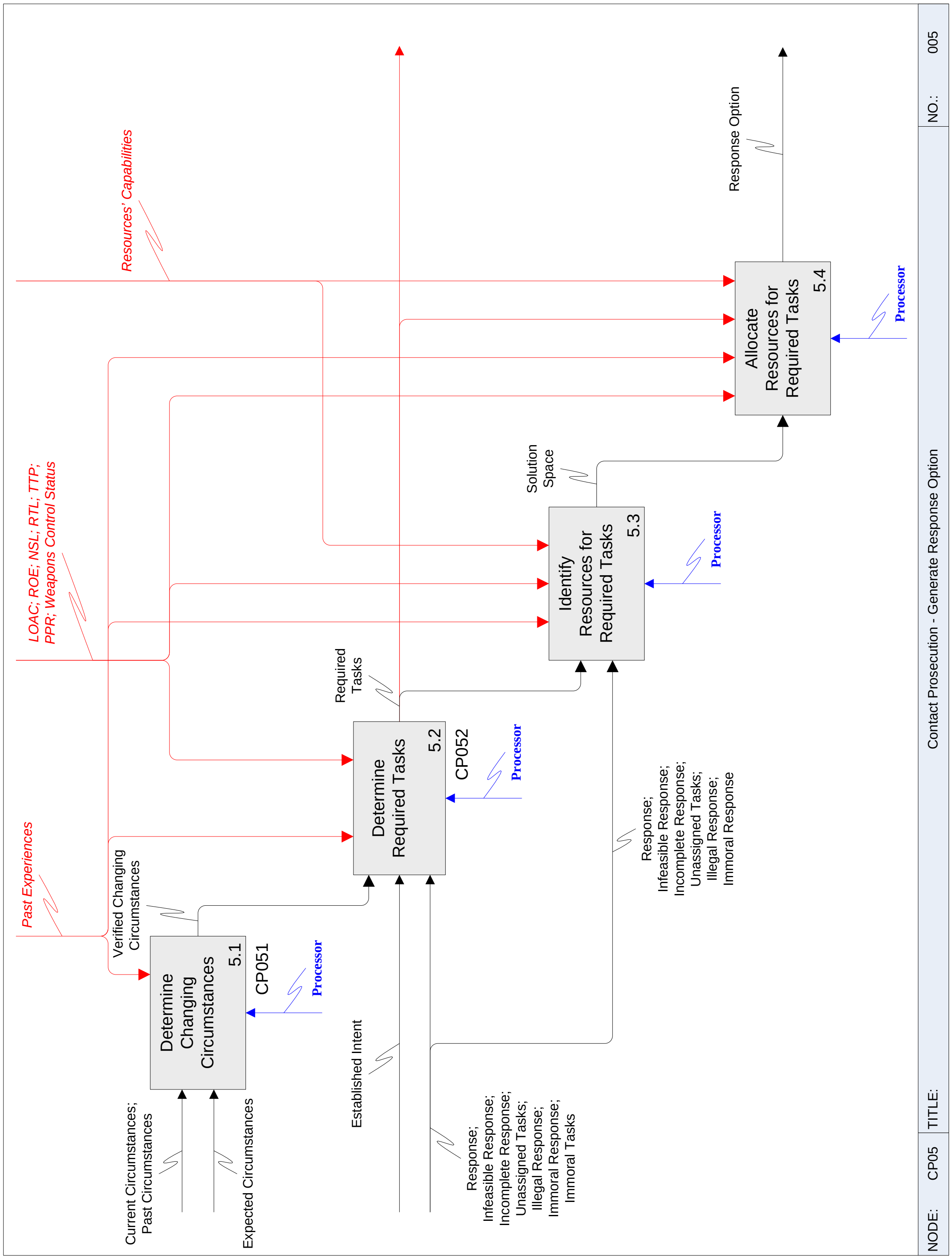

Figure 70. Relationship Diagram – CP05

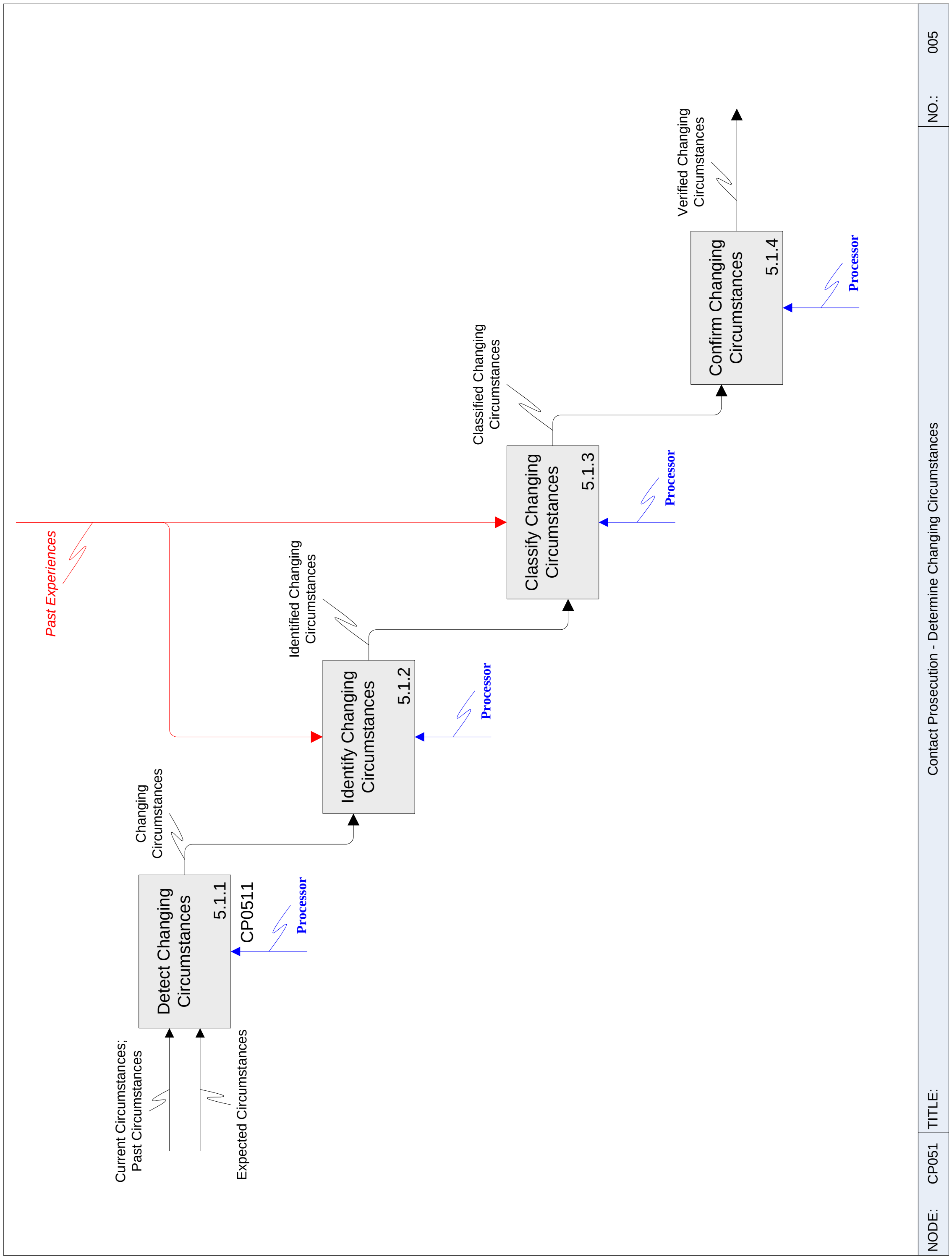

Figure 71. Relationship Diagram – CP051

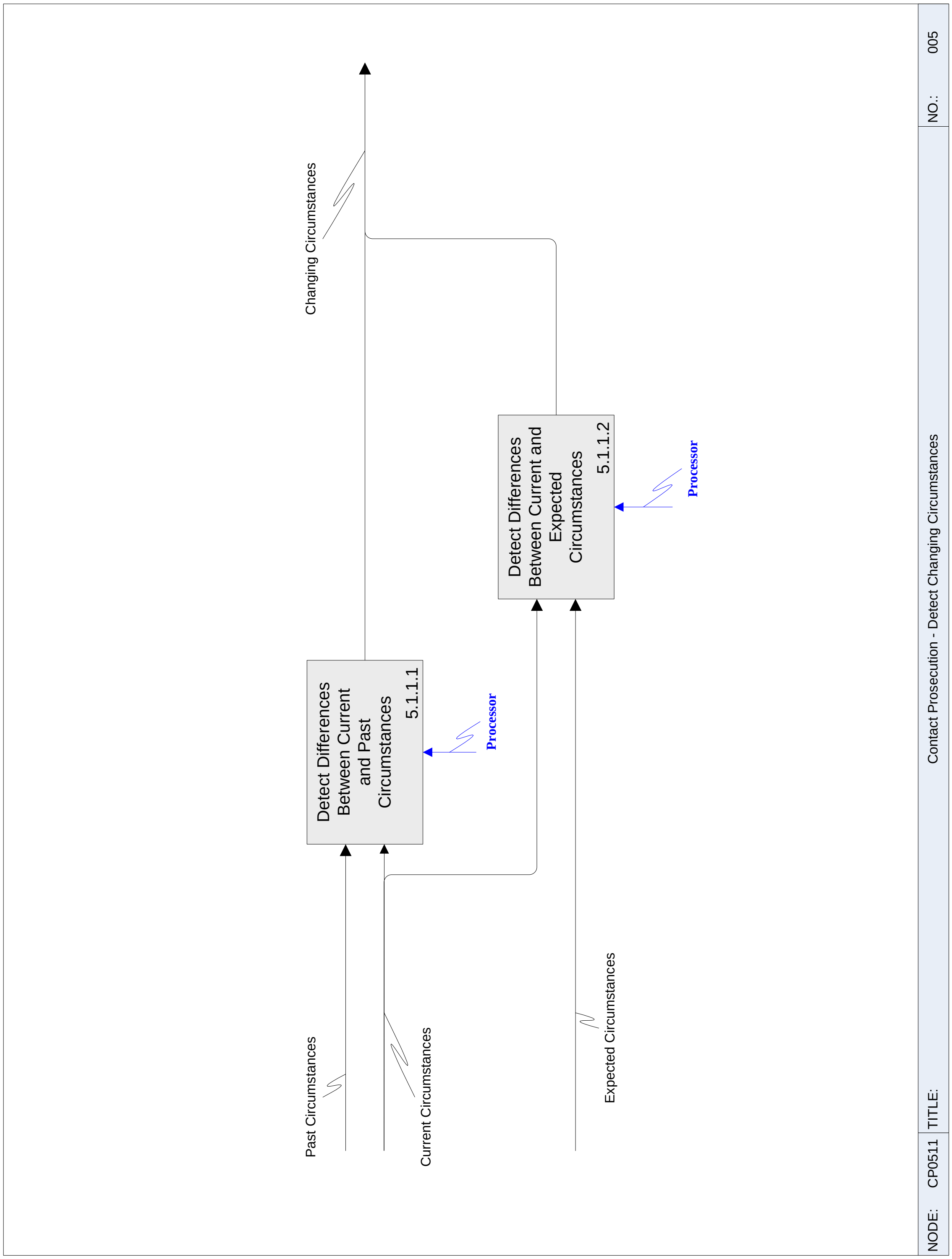

Figure 72. Relationship Diagram – CP0511

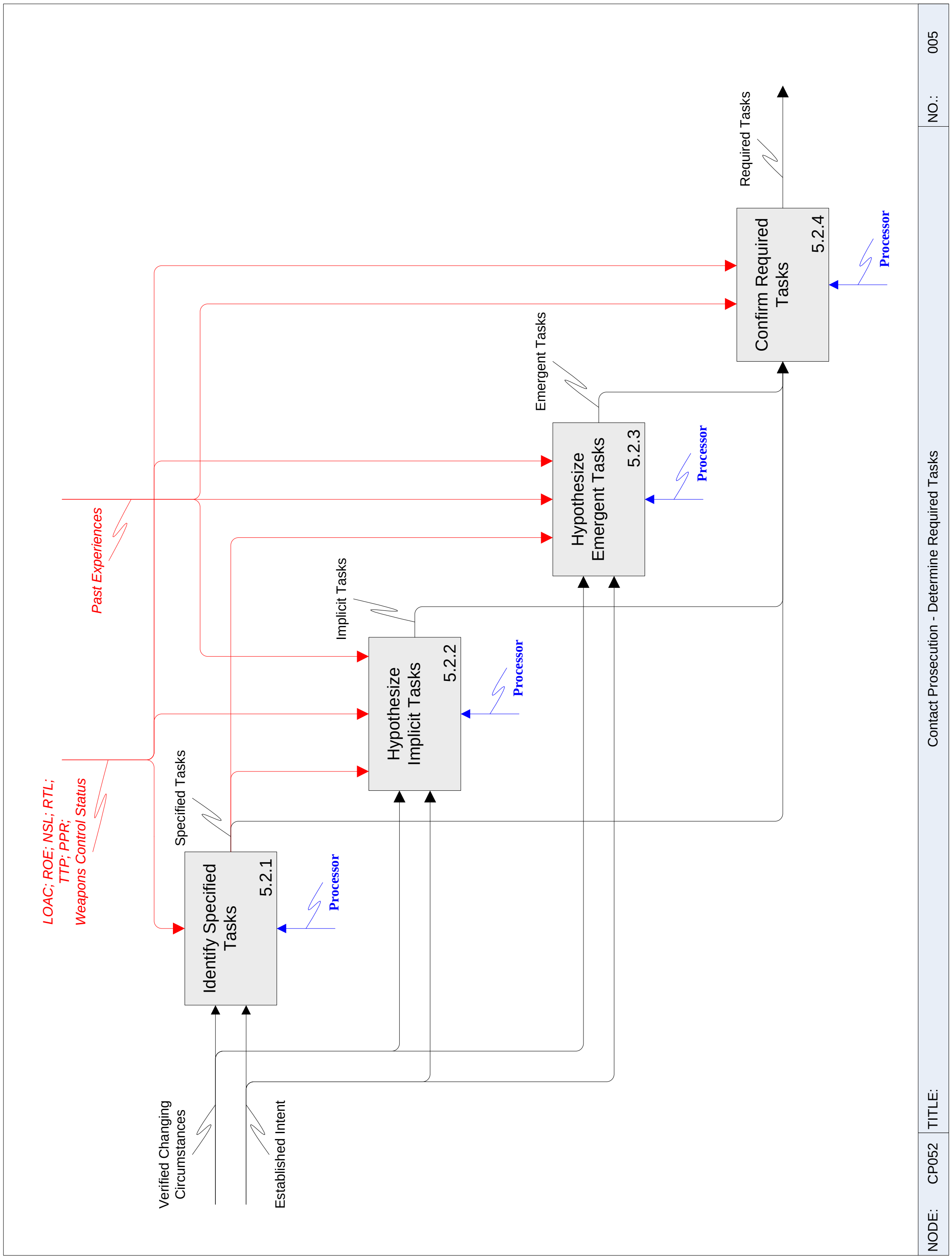

Figure 73. Relationship Diagram – CP052

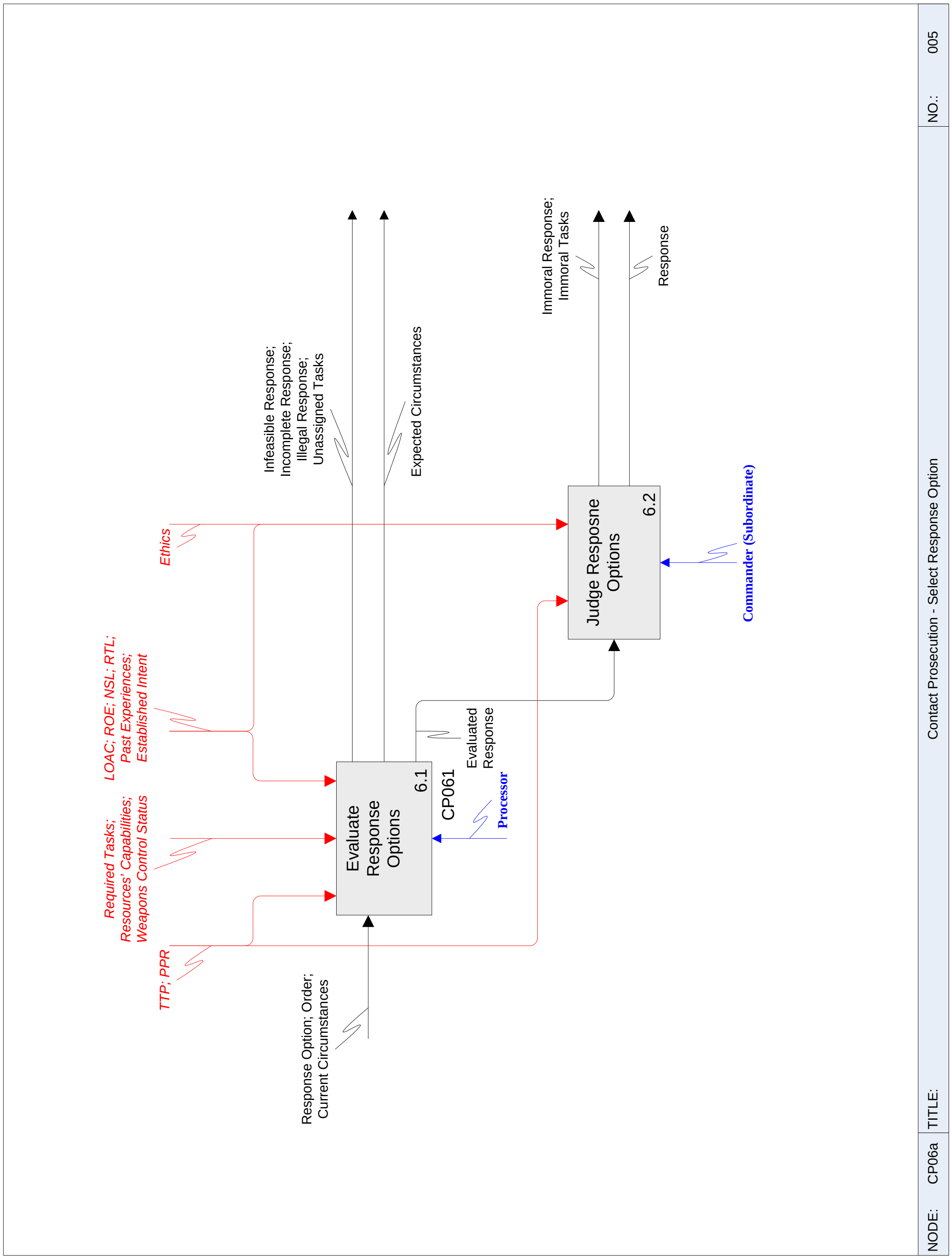

Figure 74. Relationship Diagram – CP06a

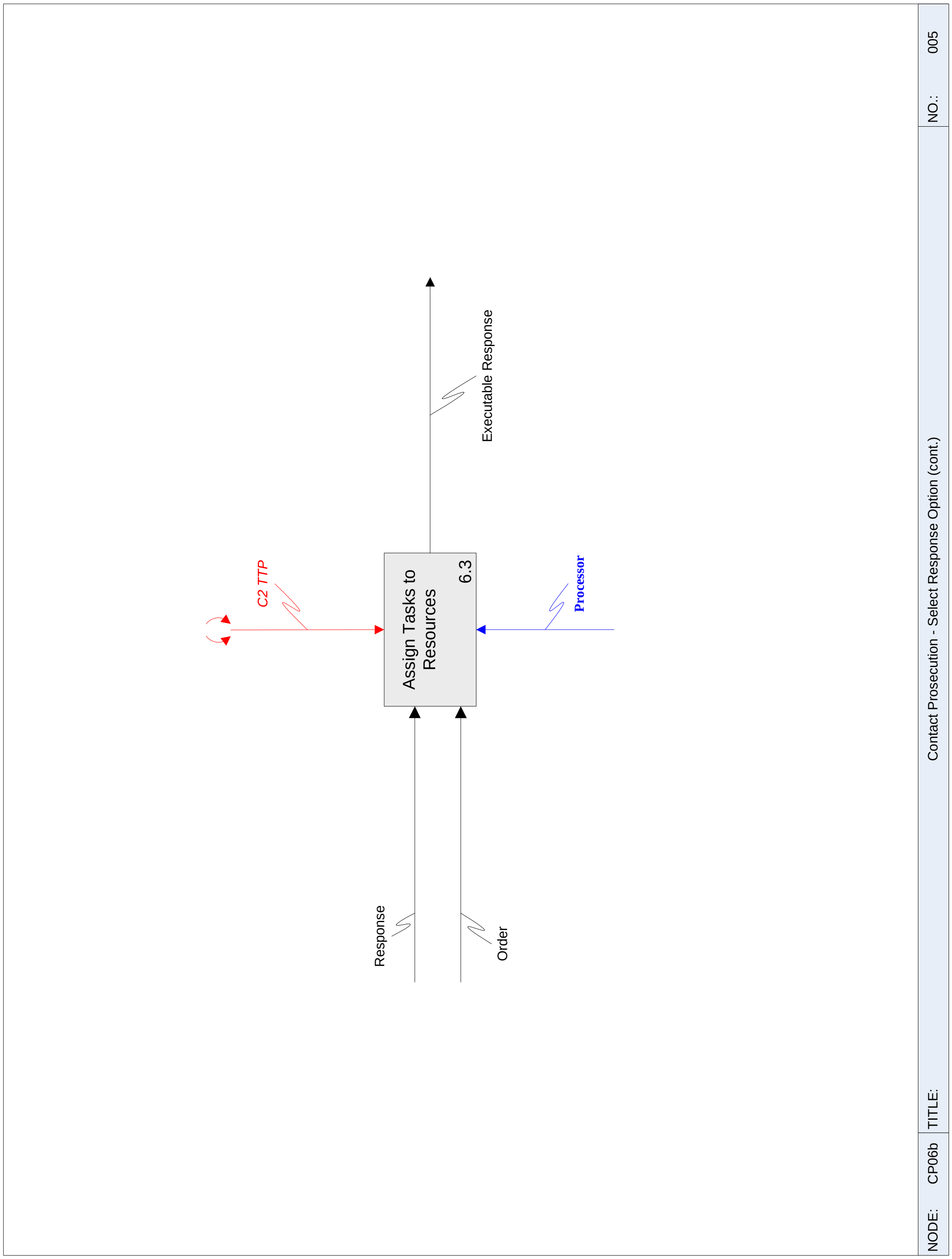

Figure 75. Relationship Diagram – CP06b

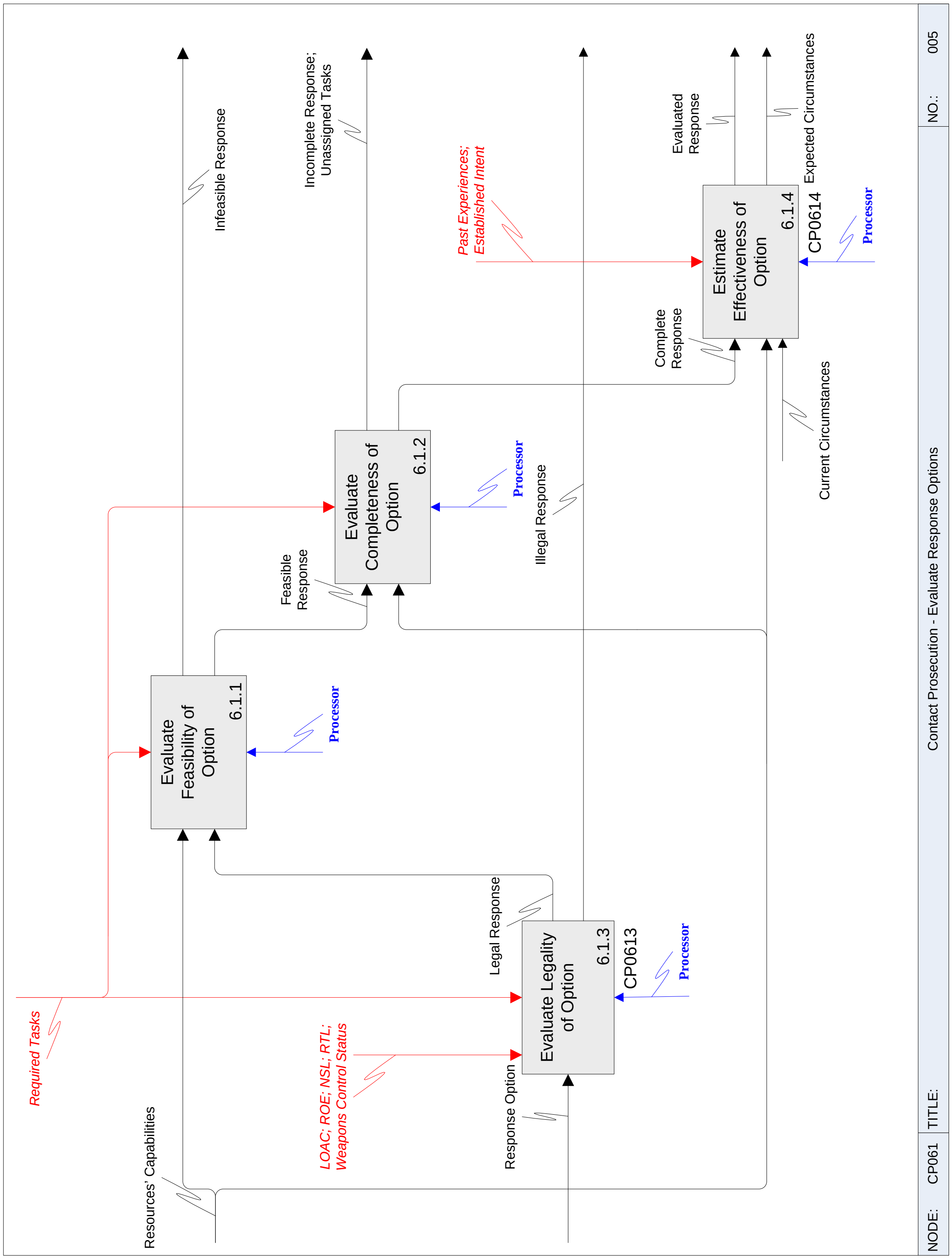

Figure 76. Relationship Diagram - CP061

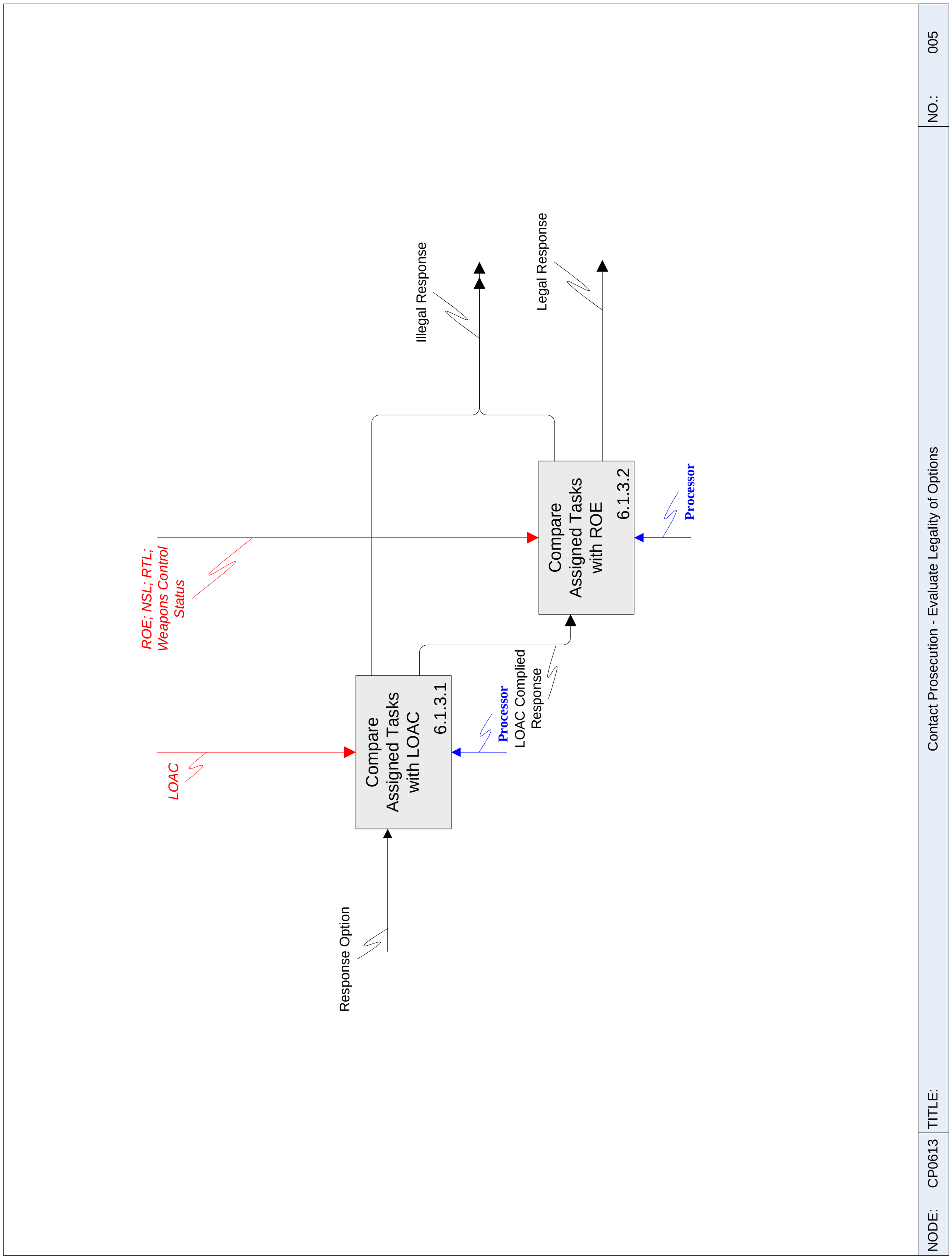

Figure 77. Relationship Diagram – CP0613

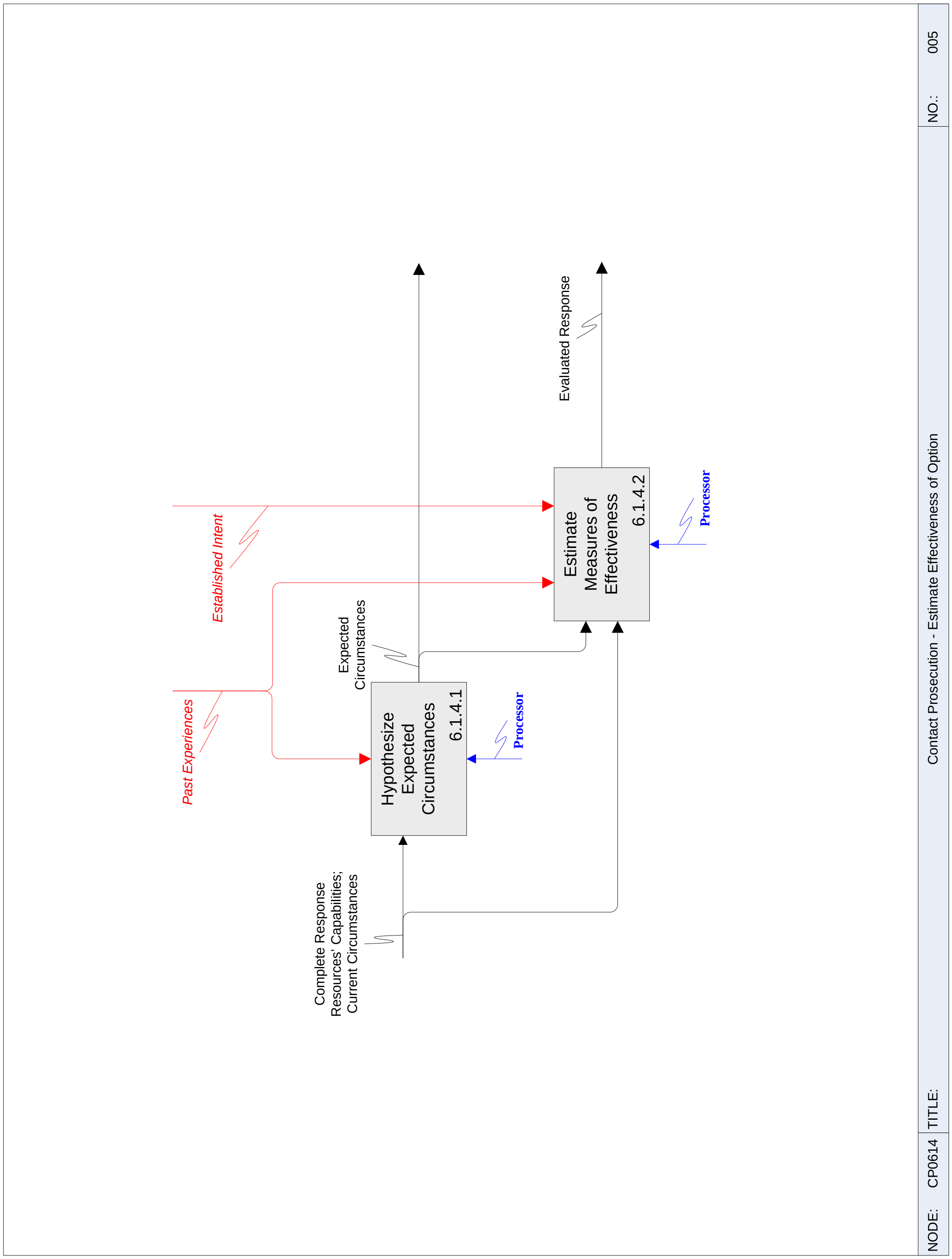

Figure 78. Relationship Diagram – CP0614

Function		Output	Required Inputs	Required Controls
1.0	**Transport Information**	- Transported Data	- Transport Data	N/A
2.0	**Process Information**	- Transport Data	- Response Option	- Communication Protocols
			- Response	- Communication Protocols
			- Order	- Communication Protocols
			- Expected Circumstances	- Communication Protocols
			- Infeasible Response	- Communication Protocols
			- Incomplete Response	- Communication Protocols
			- Unassigned Tasks	- Communication Protocols
			- Illegal Response	- Communication Protocols
			- Immoral Response	- Communication Protocols
			- Immoral Tasks	- Communication Protocols
		- Past Experiences	- Stored Data	- Communication Protocols
		- Resources' Capabilities	- Stored Data	- Communication Protocols
		- Response Option Output	- Response Option	- Communication Protocols
			- Response Option Data	- Communication Protocols
		- Assignment	- Transported Data	- Communication Protocols
		- Warning	- Transported Data	- Communication Protocols
		- Assignment Output	- Transported Data	- Communication Protocols
		- Warning Output	- Transported Data	- Communication Protocols
		- Circumstance Output	- Transported Data	- Communication Protocols
		- Intent Output	- Transported Data	- Communication Protocols
		- Response	- Transported Data	- Past Experiences
		- Infeasible Response	- Transported Data	- Past Experiences
		- Incomplete Response	- Transported Data	- Past Experiences
		- Illegal Response	- Transported Data	- Past Experiences
		- Immoral Response	- Transported Data	- Past Experiences
		- Unassigned Tasks	- Transported Data	- Past Experiences
		- Immoral Tasks	- Transported Data	- Past Experiences
		- Expected Circumstances	- Transported Data	- Past Experiences
		- Response Option	- Transported Data	- Past Experiences
		- Order	- Order	- Past Experiences
		- Current Circumstances	- Transported Data	- Past Experiences
		- Past Circumstances	- Transported Data	- Past Experiences
		- Established Intent	- Transported Data	- Past Experiences
2.1	Convert Data	- Transport Data	- Response Option	- Communication Protocols
			- Response	- Communication Protocols
			- Order	- Communication Protocols
			- Expected Circumstances	- Communication Protocols
			- Infeasible Response	- Communication Protocols
			- Incomplete Response	- Communication Protocols
			- Unassigned Tasks	- Communication Protocols
			- Illegal Response	- Communication Protocols
			- Immoral Response	- Communication Protocols
			- Immoral Tasks	- Communication Protocols
		- C2 Data	- Transported Data	- Communication Protocols
		- Past Data	- Stored Data	- Communication Protocols
		- Past Experiences	- Stored Data	- Communication Protocols

		- Resources' Capabilities	- Stored Data	- Communication Protocols
		- Input Data	- Order	- Communication Protocols
			- Sensor System Information	- Communication Protocols
			- Weapon System Information	- Communication Protocols
			- Platform Information	- Communication Protocols
		- Assignment	- Assignment Data	- Communication Protocols
		- Warning	- Warning Data	- Communication Protocols
		- Assignment Output	- Assignment Data	- Communication Protocols
		- Warning Output	- Warning Data	- Communication Protocols
		- Response Option Output	- Response Option Data	- Communication Protocols
		- Circumstance Output	- Circumstance Data	- Communication Protocols
		- Intent Output	- Intent Data	- Communication Protocols
2.1.1	Transport Conversion	- Transport Data	- Response Option	- Communication Protocols
			- Response	- Communication Protocols
			- Order	- Communication Protocols
			- Expected Circumstances	- Communication Protocols
			- Infeasible Response	- Communication Protocols
			- Incomplete Response	- Communication Protocols
			- Unassigned Tasks	- Communication Protocols
			- Illegal Response	- Communication Protocols
			- Immoral Response	- Communication Protocols
			- Immoral Tasks	- Communication Protocols
		- C2 Data	- Transported Data	- Communication Protocols
2.1.2	Storage Conversion	- Past Data	- Stored Data	- Communication Protocols
		- Past Experiences	- Stored Data	- Communication Protocols
2.1.3	Input Conversion	- Input Data	- Order	- Communication Protocols
			- Sensor System Information	- Communication Protocols
			- Weapon System Information	- Communication Protocols
			- Platform Information	- Communication Protocols
2.1.4	Output Conversion	- Assignment	- Assignment Data	- Communication Protocols
		- Warning	- Warning Data	- Communication Protocols
		- Assignment Output	- Assignment Data	- Communication Protocols
		- Warning Output	- Warning Data	- Communication Protocols
		- Response Option Output	- Response Option Data	- Communication Protocols
		- Circumstance Output	- Circumstance Data	- Communication Protocols
		- Intent Output	- Intent Data	- Communication Protocols
2.2	Evaluate Information	- Valid Past Data	- Past Data	- Past Experiences
		- Valid Input Data	- Input Data	- Past Experiences
		- Valid C2 Data	- C2 Data	- Past Experiences
2.2.1	Evaluate accuracy of information	- Accurate Data	- Past Data	- Past Experiences
			- Input Data	- Past Experiences
			- C2 Data	- Past Experiences
2.2.2	Evaluate completeness of information	- Valid Past Data	- Accurate Data	- Past Experiences
		- Valid Input Data	- Accurate Data	- Past Experiences
		- Valid C2 Data	- Accurate Data	- Past Experiences
2.3	Analyze information	- Data	- Information	- Past Experiences
			- Executable Response	- Past Experiences
			- Data	- Past Experiences

		- Assignment Data	- Information	- Past Experiences
		- Warning Data	- Information	- Past Experiences
		- Response Option Data	- Information	- Past Experiences
		- Circumstance Data	- Information	- Past Experiences
		- Intent Data	- Information	- Past Experiences
2.4	Synthesize information	- Information	- Valid Input Data	- Past Experiences
			- Valid Past Data	- Past Experiences
			- Response Option Data	- Past Experiences
			- Data	- Past Experiences
		- Response	- Valid C2 Data	- Past Experiences
		- Infeasible Response	- Valid C2 Data	- Past Experiences
		- Incomplete Response	- Valid C2 Data	- Past Experiences
		- Illegal Response	- Valid C2 Data	- Past Experiences
		- Immoral Response	- Valid C2 Data	- Past Experiences
		- Unassigned Tasks	- Valid C2 Data	- Past Experiences
		- Immoral Tasks	- Valid C2 Data	- Past Experiences
		- Expected Circumstances	- Valid C2 Data	- Past Experiences
		- Response Option	- Valid C2 Data	- Past Experiences
		- Order	- Valid C2 Data	- Past Experiences
		- Current Circumstances	- Valid C2 Data	- Past Experiences
		- Past Circumstances	- Valid C2 Data	- Past Experiences
		- Established Intent	- Valid C2 Data	- Past Experiences
3.0	**Store information**	- Stored Data	- Storage Data	N/A
4.0	**Present information**	- Presented Data	- Assignment Output	- HSI Requirements
			- Warning Output	- HSI Requirements
			- Circumstance Output	- HSI Requirements
			- Intent Output	- HSI Requirements
			- Response Option Output	- HSI Requirements
5.0	**Generate response options**	- Response Option	- Current Circumstances - Past Circumstances - Established Intent	- Past Experiences - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List - Tactics, Techniques, and Procedures - Pre-planned Responses - Resources' Capabilities
			- Current Circumstances - Expected Circumstances - Established Intent - Response	- Past Experiences - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List - Tactics, Techniques, and Procedures - Pre-planned Responses - Resources' Capabilities

			- Established Intent - Infeasible Response	- Past Experiences - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List - Tactics, Techniques, and Procedures - Pre-planned Responses - Resources' Capabilities
			- Infeasible Response	- Past Experiences - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List - Tactics, Techniques, and Procedures - Pre-planned Responses - Resources' Capabilities
			- Established Intent- Incomplete Response- Unassigned Tasks	- Past Experiences- Law of Armed Conflict- Rules of Engagement- Weapons Control Status- No Strike List- Restricted Target List- Tactics, Techniques, and Procedures- Pre-planned Responses- Resources' Capabilities
			- Incomplete Response - Unassigned Tasks	- Past Experiences - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List - Tactics, Techniques, and Procedures - Pre-planned Responses - Resources' Capabilities
			- Illegal Response	- Past Experiences - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List - Tactics, Techniques, and Procedures - Pre-planned Responses - Resources' Capabilities
			- Established Intent - Immoral Response - Immoral Tasks	- Past Experiences - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List - Tactics, Techniques, and Procedures - Pre-planned Responses - Resources' Capabilities

			- Immoral Response - Immoral Tasks	- Past Experiences - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List - Tactics, Techniques, and Procedures - Pre-planned Responses - Resources' Capabilities
		- Required Tasks	- Current Circumstances- Past Circumstances- Established Intent	- Past Experiences- Law of Armed Conflict- Rules of Engagement- Weapons Control Status- No Strike List- Restricted Target List- Tactics, Techniques, and Procedures- Pre-planned Responses
			- Current Circumstances - Expected Circumstances - Established Intent	- Past Experiences - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List - Tactics, Techniques, and Procedures - Pre-planned Responses
			- Established Intent - Infeasible Response	- Past Experiences - Tactics, Techniques, and Procedures - Pre-planned Responses
			- Established Intent - Incomplete Response - Unassigned Tasks	- Past Experiences
			- Established Intent - Immoral Response - Immoral Tasks	- Past Experiences
5.1	Determine changing circumstances	- Verified Changing Circumstances	- Current Circumstances - Past Circumstances	- Past Experiences
			- Current Circumstances - Expected Circumstances	- Past Experiences
5.1.1	Detect changing circumstances	- Changing Circumstances	- Current Circumstances - Past Circumstances	- Past Experiences
			- Current Circumstances - Expected Circumstances	- Past Experiences
5.1.1.1	Detect differences between current and past circumstances	- Changing Circumstances	- Current Circumstances - Past Circumstances	N/A
5.1.1.2	Detect differences between current and expected circumstances	- Changing Circumstances	- Current Circumstances - Expected Circumstances	N/A
5.1.2	Identify changing circumstances	- Identified Changing Circumstances	- Changing Circumstances	- Past Experiences

5.1.3	Classify changing circumstances	- Classified Changing Circumstances	- Identified Changing Circumstances	- Past Experiences
5.1.4	Confirm changing circumstances	- Verified Changing Circumstances	- Classified Changing Circumstances [X2]	N/A
5.2	Determine required tasks	- Required Tasks	- Verified Changing Circumstances- Established Intent	- Past Experiences- Law of Armed Conflict- Rules of Engagement- Weapons Control Status- No Strike List- Restricted Target List- Tactics, Techniques, and Procedures- Pre-planned Responses
			- Established Intent - Infeasible Response	- Past Experiences - Tactics, Techniques, and Procedures - Pre-planned Responses
			- Established Intent - Incomplete Response - Unassigned Tasks	- Past Experiences
			- Established Intent - Immoral Response - Immoral Tasks	- Past Experiences
5.2.1	Identify specified tasks	- Specified Tasks	- Verified Changing Circumstances - Established Intent	- Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List - TTPs - PPRs
5.2.2	Hypothesize implicit tasks	- Implicit Tasks	- Verified Changing Circumstances - Established Intent	- Past Experiences - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List - TTPs - PPRs - Specified Tasks
5.2.3	Hypothesize emergent tasks	- Emergent Tasks	- Verified Changing Circumstances - Established Intent	- Past Experiences - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List - TTPs - PPRs - Specified Tasks
5.2.4	Confirm Required Tasks	- Required Tasks	- Established Intent - Infeasible Response	- Past Experiences - TTPs - PPRs
			- Established Intent - Incomplete Response - Unassigned Tasks	- Past Experiences
			- Established Intent- Immoral Response- Immoral Tasks	- Past Experiences

5.3	Identify resources for required tasks	- Solution Space	- Required Tasks	- Past Experiences - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List - TTPs - PPRs - Resources' Capabilities
			- Response	- Past Experiences - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List - Tactics, Techniques, and Procedures - Pre-planned Responses - Resources' Capabilities
			- Infeasible Resposne	- Past Experiences - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List - Tactics, Techniques, and Procedures - Pre-planned Responses - Resources' Capabilities
			- Unassigned Tasks - Incomplete Response	- Past Experiences - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List - Tactics, Techniques, and Procedures - Pre-planned Responses - Resources' Capabilities
			- Illegal Response	- Past Experiences - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List - Tactics, Techniques, and Procedures - Pre-planned Responses - Resources' Capabilities
			- Immoral Response	- Past Experiences- Law of Armed Conflict- Rules of Engagement- Weapons Control Status- No Strike List- Restricted Target List- Tactics, Techniques, and Procedures- Pre-planned Responses- Resources' Capabilities

5.4	Allocate resources for required tasks	- Response Option	- Solution Space	- Past Experiences - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List - Tactics, Techniques, and Procedures - Pre-planned Responses - Resources' Capabilities - Required Tasks
6.0	**Select response options**	Executable Response	- Response Option - Resources' Capabilities	- Past Experiences - Established Intent - Required Tasks - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List - Tactics, Techniques, and Procedures - Pre-planned Responses - Ethics
		Expected Circumstances	- Complete Response - Resources' Capabilities - Current Circumstances	- Past Experiences - Required Tasks - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List
6.1	Evaluate response options	- Evaluated Response	- Response Option - Resources' Capabilities - Current Circumstances	- Past Experiences - Established Intent - Required Tasks - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List
		Expected Circumstances	- Complete Response - Resources' Capabilities - Current Circumstances	- Past Experiences - Required Tasks - Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List
6.1.1	Evaluate feasibility of options	- Feasible Response - Infeasible Response	- Legal Response - Resources' Capabilities	- Required Tasks
6.1.2	Evaluate completeness of options	- Complete Response - Incomplete Response	- Feasible Response - Resources' Capabilities	- Required Tasks
		- Unassigned Tasks	- Feasible Response - Resources' Capabilities	- Required Tasks
6.1.3	Evaluate legality of options	- Legal Response - Illegal Response	- Response Option	- Law of Armed Conflict - Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List

6.1.3.1	Compare assigned tasks with law of armed conflict	- LOAC Complied Response - Illegal Response	- Response Option	- Law of Armed Conflict
6.1.3.2	Compare assigned tasks with rules of engagement	- Legal Response - Illegal Response	- LOAC Complied Response	- Rules of Engagement - Weapons Control Status - No Strike List - Restricted Target List
6.1.4	Estimate effectiveness of option	- Evaluated Response	- Complete Response - Resources' Capabilities - Current Circumstances	- Past Experiences - Established Intent
		- Expected Circumstances	- Complete Response - Resources' Capabilities - Current Circumstances	- Past Experiences
6.1.4.1	Hypothesize expected circumstances	- Expected Circumstances	- Complete Response - Resources' Capabilities	- Past Experiences
6.1.4.2	Estimate measures of effectiveness	- Evaluated Response	- Complete Response - Resources' Capabilities - Current Circumstances - Expected Circumstances	- Past Experiences - Established Intent
6.2	Judge response options	- Response - Immoral Response	- Evaluated Response	- Past Experiences - Established Intent - Ethics
6.3	Assign tasks to resources	- Executable Response	- Response	- Tactics, Techniques, and Procedures - Pre-planned Responses

Table 33. Contact Prosecution – Function Activation and Control

B. ARENA® MODELS OF THE CONTACT PROSECUTION PROCESS

To demonstrate the feasibility of using the developed architectural framework to analyze and compare alternative designs, Arena®, version 10.0, was used. Arena® is a discrete-event modeling and simulation software developed by Rockwell Automation, Inc. This section presents the developed Arena® models of the contact prosecution process and the subsequent simulation results.

1. The Models

Arena® was used to develop two models, one for each of the alternative architectures of the system. The models represent a portion of the notional contact prosecution process discussed in Chapter VII and detailed in the previous sections of this thesis. The top-level diagram, which is identical for both models, is presented in Figure

79. The diagram shows the three top-level functions which are a part of the process: *Transport Information*, *Process Information,* and *Select Response Options.* The other items in the diagram are for the creation and disposal of the entities (i.e., response options and responses) flowing through the model, as well as for measuring and controlling the flow of the entities.

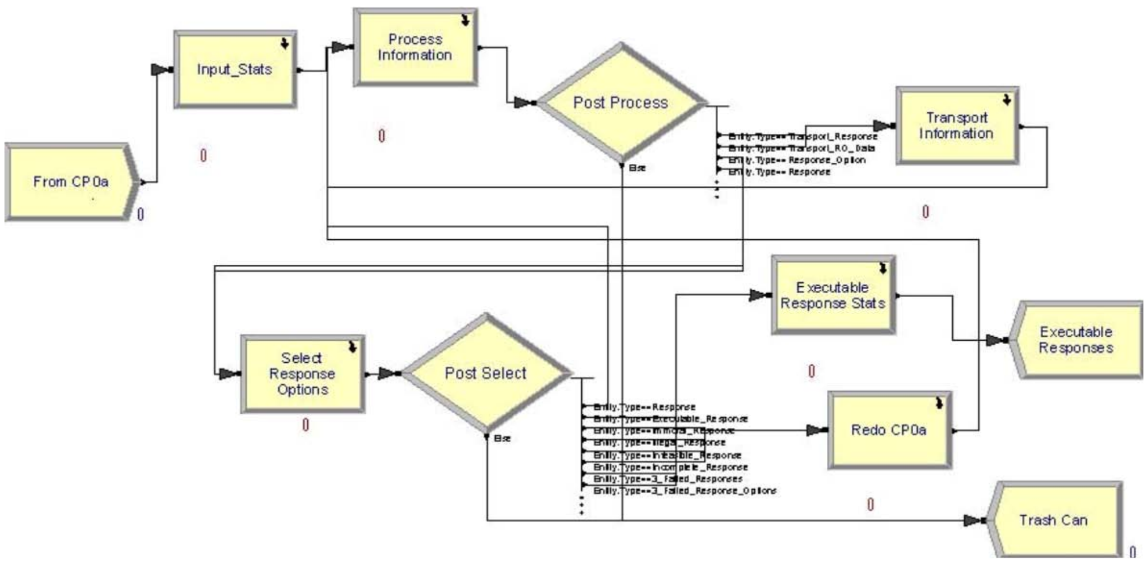

Figure 79.   Arena® Model – Top-level

In both models, the first step is the creation of a response option. The response option is then copied; the number of copies determined by the selected architecture. The response option and its copies are then processed, transported, and processed again to serve as an input to *Select Response Options*. The first response to arrive at a particular line of mechanisms is used. All other copies sent to such line of mechanisms are discarded. The response option is then evaluated and judged. If the response option is determined to be either illegal, infeasible, incomplete, or immoral, it is sent to Redo CP0a to serve as input for the generation of another response option. If it is determined to be legal, feasible, incomplete, and moral, it becomes a response. The response is copied multiple times, again as determined by the selected architecture. The response is then processed, transported, and processed to serve as input for *Select Response Options* where tasks are assigned to resources. Again, the first response to arrive at a particular

line of mechanisms is used while all other responses are discarded. Once the assignments are complete, the response becomes an executable response and the model is complete.

The use of Arena® to model the selected portion of the contact prosecution process required the adaptation of the previously generated relationship diagrams along with the integration of the identified functional activations. Whenever possible, the author attempted to construct the Arena® models to flow, both visually and logically, as the previously generated relationship diagrams. In addition, many logical decision points were included throughout the model to control the flow of the entities (e.g., response options and responses).

A major challenge faced, due to the selection of Arena® as the modeling and simulation software, was the modeling of the systems resources. Arena® does provide a simple module for managing resources, to include the number available to the system and the rules for each resources use. The software also allows for a straight-forward assignment of a resource, or a set of resources, to a given function. The difficulty with using Arena® arose when trying to model the parallel paths associated with a distributed network. To overcome this challenge, most functions were further dissected logically to ensure a particular entity was assigned the corresponding mechanism. For example, as shown in Figure 80. and Figure 81. , responses being transported were first separated according to their destination line-of-mechanisms in *Select Response Options* and then according to the specific link to be used for transport. This was done to ensure that the entities were properly delayed and queues for future mechanisms were properly established. This approach, however, makes the model cumbersome and difficult to scale (e.g., adding more parallel subordinate commanders). Though a better approach to account for these difficulties may have been possible using Arena®, such application was beyond the skill of the author.

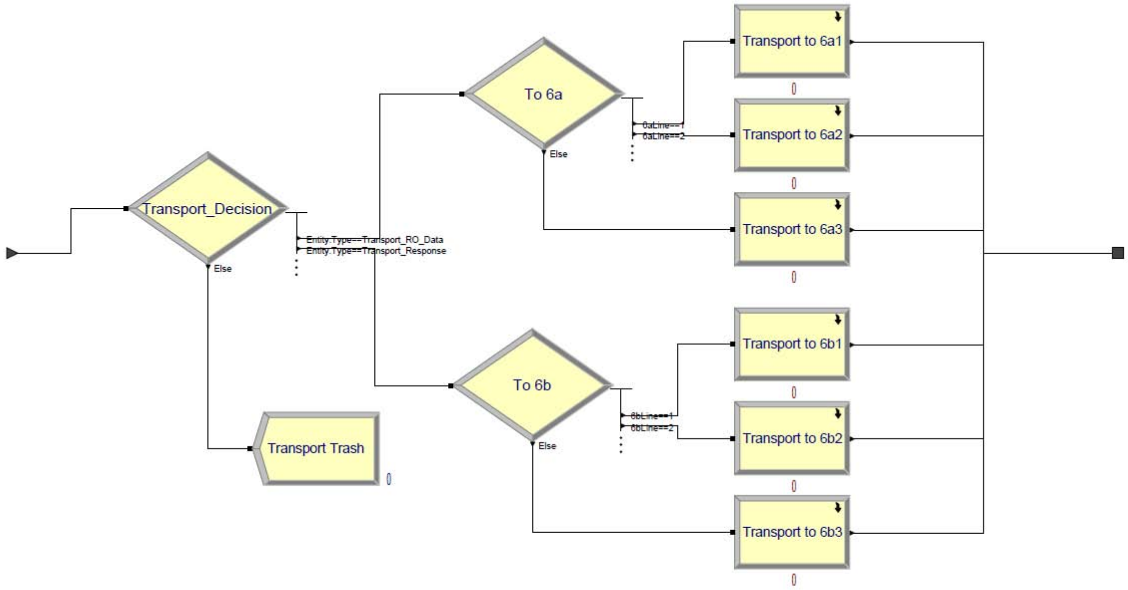

Figure 80. Arena® Model – Transport Information

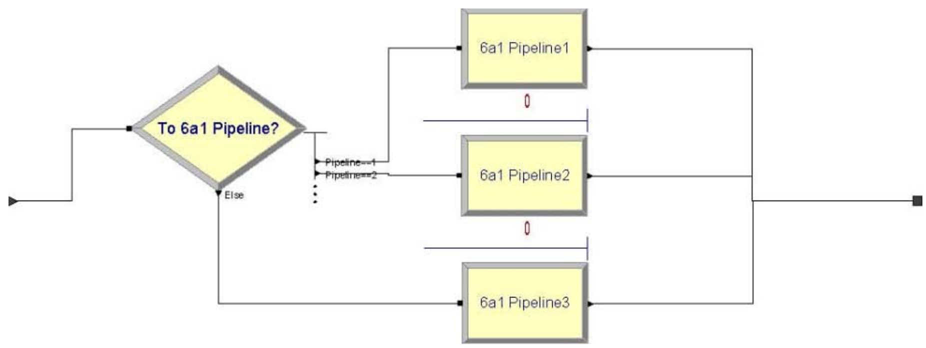

Figure 81. Arena® Model – Transport to 6a1

The model for Alternative #2 was developed first. From this, the model for Alternative #1 was created by reducing the number of copies of response options and responses generated. In essence, for Alternative #1, copies of response options and responses were made only to follow the top line-of-mechanisms for *Select Response Options* of Alternative #2, when appropriate. This approach ensured the attributes and characteristics of each function and resource remained consistent between models. The only other significant changes between models involved the respective collection of data. Figure 82. through Figure 86. present selected views of the Arena® models developed.

Table 34. shows the distributions and resources associated with each function. The section following discusses the simulations and results.

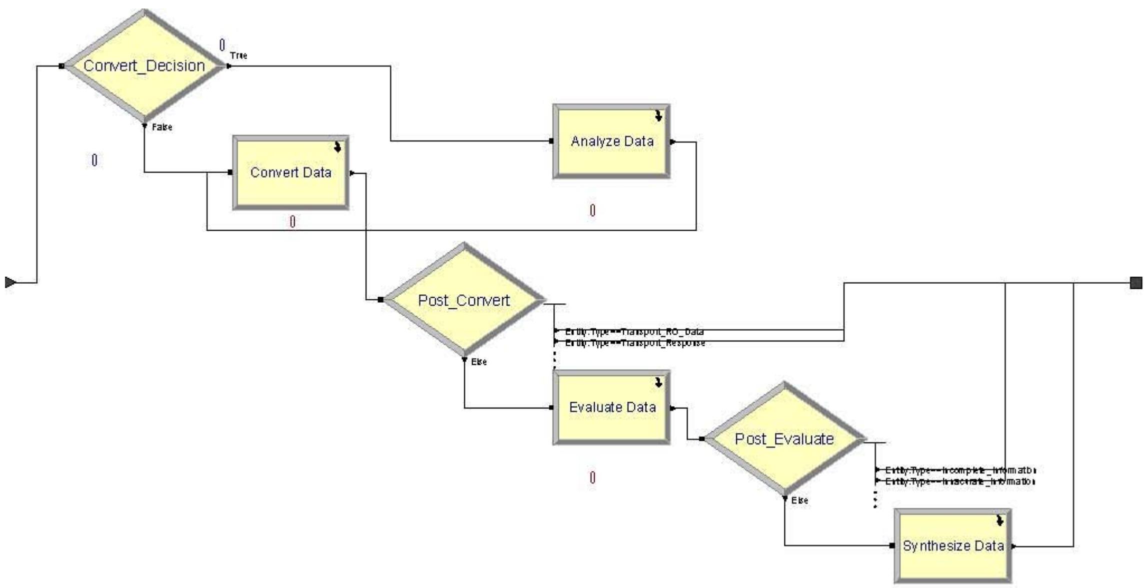

Figure 82. Arena® Model – Process Information

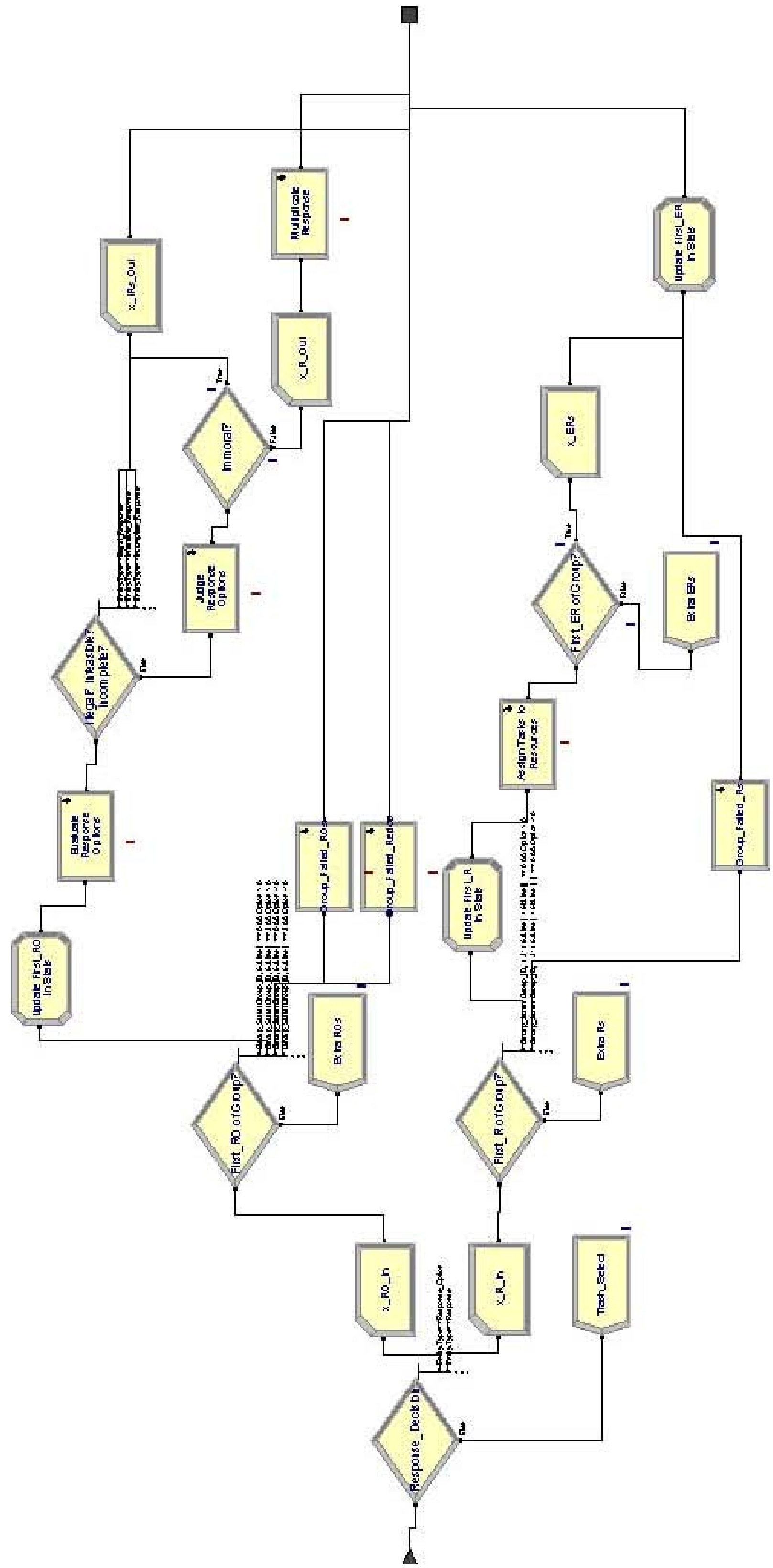

Figure 83. Arena® Model – Select Response Option

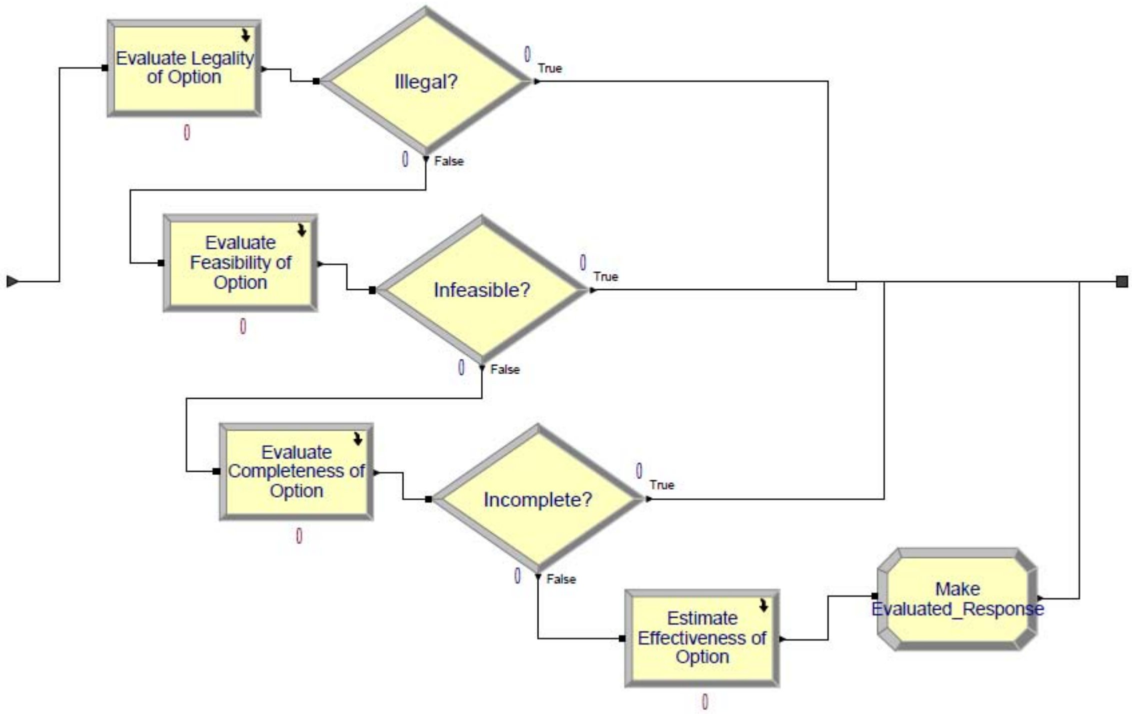

Figure 84. Arena® Model – Evaluate Response Options

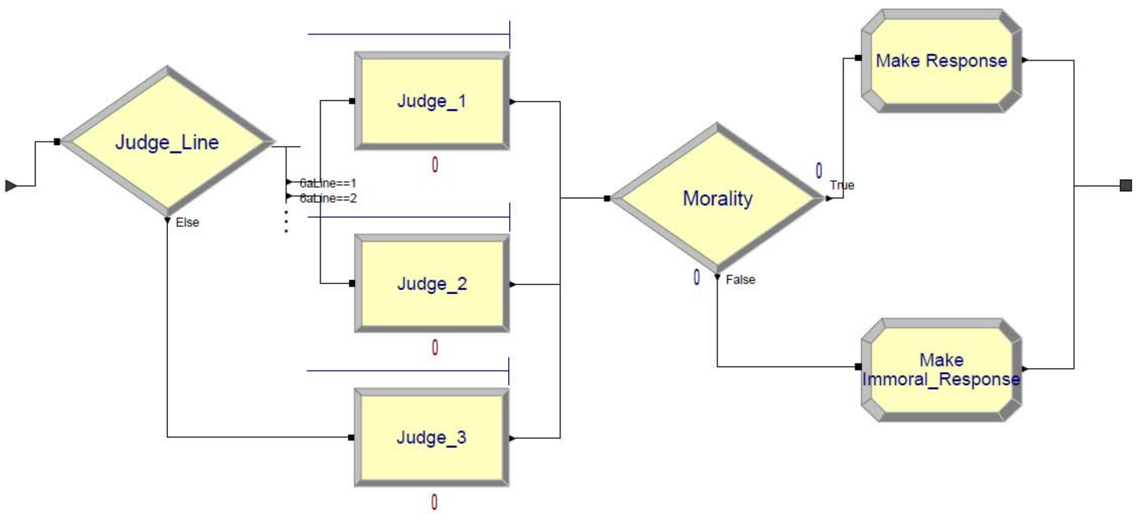

Figure 85. Arena® Model – Judge Response Options

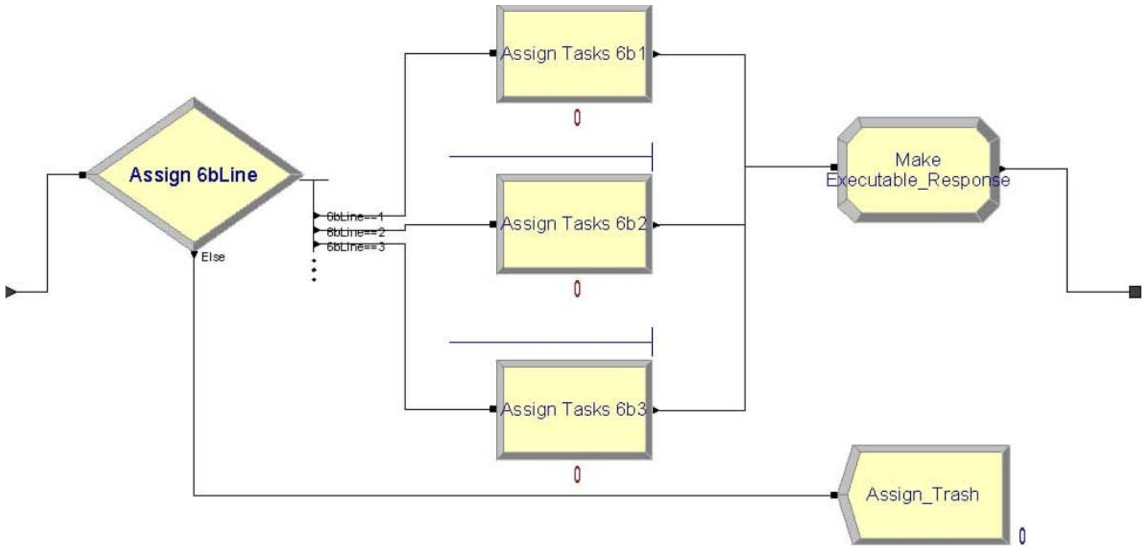

Figure 86. Arena® Model – Assign Tasks to Resources

	Function	Distribution	Resources
1.0	Transport Information	Normal (0.0005, 0.0001)	Links – 3 per line-of-mechanisms
2.1.1	Transport Conversion	Normal (0.05, 0.01)	Processor – 1 per link per line-of-mechanisms
2.2.1	Evaluate Accuracy of Data	Normal (0.05, 0.01)	Processors – 1 per line-of-mechanisms
2.2.2	Evaluate Completeness of Data	Normal (0.05, 0.01)	Processors – 1 per line-of-mechanisms
2.3	Analyze Information	Normal (1.0, 0.2)	Processors – 1 per line-of-mechanisms
2.4	Synthesize Information	Normal (0.2, 0.02)	Processors – 2 per line-of-mechanisms
6.1.1	Evaluate feasibility of options	Normal (0.08, 0.02)	Processors – 1 per line-of-mechanisms
6.1.2	Evaluate completeness of options	Normal (0.05, 0.01)	Processors – 1 per line-of-mechanisms
6.1.3.1	Compare assigned tasks with law of armed conflict	Normal (0.05, 0.01)	Processors – 1 per line-of-mechanisms
6.1.3.2	Compare assigned tasks with rules of engagement	Normal (0.05, 0.01)	Processors – 1 per line-of-mechanisms
6.1.4.1	Hypothesize expected circumstances	Normal (1.0, 0.2)	Processors – 1 per line-of-mechanisms
6.1.4.2	Estimate measures of effectiveness	Normal (0.8, 0.2)	Processors – 1 per line-of-mechanisms
6.2	Judge Response Options	Normal (3.0, 1.0)	Subordinate Commander – 1 per line-of-mechanisms
6.3	Assign Tasks to Resources	Normal (5.0, 1.0)	Processors – 4 per line-of-mechanisms
N/A	Redo CP06a (e.g., make new response option)	Triangle (3.0, 5.0, 10.0)	N/A

Table 34. Associated Distributions and Resources for Functions

2. The Simulation

The objective of simulating the two models was to demonstrate possible performance differences in the alternative architectures. A combination of three MoMs from the systems objective hierarchy was selected to highlight such differences. First, the sum of MoP 5.2.2.2, time between response option being developed and response decision, and MoP 6.2.1, time between order of response execution by decision-

authorized entity and completion of allocations by allocation-authorized entity, was recorded for each alternative design. Second, MoCE 5.5, consistency of response between decision-authorized entities, was also recorded.

Once both models were complete, thirty replications were conducted for each. Each replication began with a warm-up time of three simulation-minutes to fill queues and task resources followed by ten simulation-minutes in which data was collected. For both alternative models, response options were created with inter-arrival times following an exponential distribution with a mean of 1/5 s^{-1}. As a result, approximately 100+ response options were created and served as input during the ten operational simulation-minutes.

The minimum time from response option creation until the generation of an associated executable response, the sum of MoP 5.2.2.2 and MoP 6.2.1, was recorded for each response option and, in the case of Alternative #2, for each line of *Select Response Option* mechanisms. In addition, for Alternative #2, the executable responses for each response option were compared to determine consistency (i.e., MoCE 5.5). Results for the model of Alternative #1 are presented in Table 35. The first column denotes the replication number. The second column denotes the average time for one of the approximately 100+ response options to generate an executable response. The third column denotes the equivalent minimum time for the replication while the fourth column denotes the equivalent maximum time. The fifth column shows the number of response options created during the replication. The sixth column shows the number of executable responses generated from the response options for the replication. Finally, the seventh column presents the percentage of response options which generate executable responses in each ten simulation-minute replication.

	Time from Response Option to Executable Response			Response Options Generated	Executable Responses	Response Percentage
#	Avg	Min	Max			
1	***15.260***	9.556	34.983	132	129	97.73%
2	***15.881***	8.517	39.135	131	125	95.42%
3	***18.508***	9.653	48.906	138	136	98.55%
4	***17.451***	7.466	44.437	131	128	97.71%
5	***16.534***	8.528	39.753	138	131	94.93%
6	***20.417***	9.235	67.205	134	129	96.27%
7	***14.967***	8.783	47.998	116	112	96.55%
8	***16.548***	8.972	46.633	122	118	96.72%
9	***14.568***	8.915	27.816	108	107	99.07%
10	***17.508***	9.194	51.854	133	126	94.74%
11	***16.096***	8.003	39.235	115	114	99.13%
12	***15.195***	9.007	30.510	117	113	96.58%
13	***15.068***	7.138	38.178	124	121	97.58%
14	***18.575***	8.999	58.073	141	138	97.87%
15	***14.755***	9.602	32.627	124	122	98.39%
16	***15.021***	8.550	30.509	112	109	97.32%
17	***16.670***	7.295	38.159	120	116	96.67%
18	***15.047***	8.547	36.435	113	110	97.35%
19	***17.186***	9.142	37.730	111	108	97.30%
20	***16.971***	9.774	40.362	137	134	97.81%
21	***14.671***	8.778	34.410	103	101	98.06%
22	***16.787***	10.096	37.522	125	123	98.40%
23	***16.435***	7.726	36.008	127	124	97.64%
24	***14.987***	10.117	29.551	111	107	96.40%
25	***16.714***	7.626	51.489	129	128	99.22%
26	***15.492***	7.689	34.432	113	111	98.23%
27	***16.877***	8.968	38.586	133	133	100.00%
28	***16.256***	9.216	35.771	129	124	96.12%
29	***17.875***	8.097	43.541	116	113	97.41%
30	***15.085***	9.358	31.910	110	106	96.36%

Table 35. Alternative #1 Arena® Results

Table 36. presents results of the Alternative #2 model, specifically the minimum time from response option to executable response. Again, the first column denotes the replication number. To understand the second through tenth columns, the reader must first understand the ideas of grouping and consistency as they apply to this thesis and

simulation. At the beginning of the Alternative #2 model, one response option is copied multiple times both for the multiple lines-of-mechanisms in *Select Response Options* and for the multiple links used in *Transport Information*. Such response option and copies are a deemed a group. When during *Select Response Options* a response option is deemed illegal, infeasible, incomplete, or immoral, it is return to *Generate Response Options* to serve as input for a new response option. If all or none of the response options return to *Generate Response Options* then the group of executable responses which will be generated from the original response option will be consistent. Otherwise, they will be inconsistent.

The second, third, and fourth column present the results for all groups of executable responses, the fifth, sixth, and seventh for all groups of consistent executable responses, and the eighth, ninth, and tenth for all groups of inconsistent executable responses. In each column group, the first column denotes the average minimum time, for each group of responses, from response option to executable response. The second and third in each column group present minimum time, for each group of responses, from response option to executable response, minimum and maximum respectively.

	Minimum time, for group of responses, from response option to executable response: All groups			**Minimum time, for group of responses, from response option to executable response:** Consistent groups			**Minimum time, for group of responses, from response option to executable response:** Inconsistent groups		
#	**Avg**	**Min**	**Max**	**Avg**	**Min**	**Max**	**Avg**	**Min**	**Max**
1	***19.048***	7.996	37.035	19.284	7.996	37.035	17.791	9.222	34.587
2	***14.189***	8.738	26.970	14.267	8.738	26.970	13.459	9.495	21.464
3	***15.278***	8.014	37.152	15.516	8.014	37.152	14.115	8.296	29.317
4	***15.024***	7.408	32.707	15.141	7.408	32.707	14.348	9.630	25.869
5	***15.772***	8.589	34.415	15.723	8.589	34.415	16.056	9.309	31.758
6	***15.316***	6.398	31.776	15.308	6.398	31.776	15.402	9.876	26.314
7	***16.772***	8.968	39.589	16.360	8.968	38.538	19.707	10.777	39.589
8	***11.055***	7.670	16.242	11.085	7.670	16.242	10.790	9.439	13.843
9	***13.173***	8.095	24.574	13.157	8.095	24.574	13.307	8.704	18.073
10	***25.478***	7.266	52.300	25.181	7.266	51.403	27.992	9.497	52.300
11	***13.153***	7.861	25.144	12.694	7.861	25.144	15.969	9.374	22.967
12	***13.778***	8.139	24.705	13.695	8.139	24.705	14.286	9.576	21.525
13	***13.770***	8.115	27.319	13.756	8.115	27.319	13.874	10.611	23.587
14	***11.795***	7.412	20.006	11.792	8.475	20.006	11.812	7.412	15.442
15	***14.124***	8.049	24.063	14.089	8.049	24.063	14.477	9.102	23.347
16	***15.108***	7.396	29.288	14.924	7.396	29.288	16.383	10.647	27.649
17	***15.551***	8.813	27.900	15.366	8.813	27.900	16.771	9.510	25.429
18	***13.148***	6.963	23.288	13.170	6.963	23.288	12.946	8.659	19.265
19	***13.883***	7.287	28.151	13.959	7.287	28.151	13.384	9.623	19.047
20	***14.966***	8.309	25.373	14.520	8.309	23.536	16.971	9.009	25.373
21	***18.693***	6.994	32.648	18.249	6.994	31.376	21.548	9.604	32.648
22	***14.285***	8.038	29.258	13.850	8.038	27.662	16.920	10.098	29.258
23	***11.910***	7.307	20.099	11.870	7.307	20.099	12.339	7.970	14.335
24	***14.498***	8.088	30.613	14.035	8.088	30.613	16.881	8.861	29.789
25	***16.068***	8.488	32.353	15.758	8.488	29.285	17.249	9.927	32.353
26	***14.728***	6.373	29.513	14.715	8.155	27.229	14.797	6.373	29.513
27	***13.283***	8.271	21.733	13.219	8.271	21.733	13.628	9.407	20.754
28	***14.582***	7.251	28.030	14.398	7.251	28.030	16.160	8.553	26.094
29	***14.810***	8.797	37.425	14.522	8.797	37.425	16.285	9.186	31.815
30	***15.405***	8.628	35.001	15.579	8.631	35.001	14.486	8.628	27.359

Table 36. Alternative #2 Arena® Results – Minimum Time from Response Option to Executable Response

Table 37. presents results of the Alternative #2 model, specifically the time interval between executable responses. The second through fifth columns denote time intervals for groups of consistent executable responses while the sixth through eighth

columns denote time intervals for groups of inconsistent executable responses. In each column group, the first column denotes the average time between an executable response in the group and the next subsequent executable response. The second and third columns of each column group denote the minimum and maximum time between an executable response in the group and the next subsequent executable response, respectively.

	Interval between Responses (Groups of Consistent Reponses)			**Interval between Responses** (Groups of Inconsistent Responses)		
#	**Avg**	**Min**	**Max**	**Avg**	**Min**	**Max**
1	4.338	0.171	11.529	18.808	4.722	33.395
2	3.577	0.074	10.386	17.229	8.891	30.378
3	4.411	0.498	14.263	24.299	10.299	49.969
4	3.809	0.103	12.178	18.906	2.087	29.842
5	4.351	0.149	18.226	19.483	9.028	43.081
6	4.618	0.319	14.703	22.753	11.123	37.728
7	4.559	0.291	19.228	23.516	8.647	49.527
8	2.552	0.868	5.087	17.003	13.946	27.850
9	3.341	0.292	7.813	19.546	9.783	56.541
10	5.742	0.217	17.996	28.281	0.315	63.333
11	3.604	0.334	9.920	20.695	12.751	44.756
12	2.848	0.227	7.650	18.143	9.593	29.001
13	4.234	0.711	14.817	20.786	13.163	36.533
14	3.273	0.165	8.751	15.596	6.710	19.708
15	3.022	0.386	10.041	19.267	10.706	29.408
16	3.433	0.364	7.874	17.091	10.535	35.511
17	3.949	0.252	14.000	22.340	11.385	43.676
18	3.079	0.337	7.605	16.004	12.472	22.337
19	3.402	0.340	9.079	16.155	9.968	28.609
20	3.564	0.332	8.577	15.955	6.795	27.760
21	3.879	0.257	11.245	19.103	5.999	33.499
22	3.523	0.143	9.952	15.451	6.770	23.675
23	3.248	0.282	11.943	20.385	9.618	48.725
24	5.183	0.095	17.787	19.518	7.908	40.171
25	4.416	0.124	11.017	16.062	8.284	25.313
26	3.801	0.163	10.890	18.861	9.266	39.118
27	3.446	0.078	9.017	16.399	6.085	39.335
28	3.632	0.372	10.090	20.283	12.561	32.125
29	3.179	0.524	8.265	15.868	8.301	26.766
30	4.250	0.360	13.666	20.276	9.825	32.209

Table 37. Alternative #2 Arena® Results – Time Interval Between Executable Responses

Table 38. presents results of the Alternative #2 model. The second column shows the number of response options created during the replication. The third column shows the number of groups of consistent executable responses generated from the response options. The fourth column shows the number of groups of inconsistent executable responses generated from the response options. The fifth column presents the percentage of response options which generate executable responses in each ten simulation-minute replication. Finally, the sixth column presents the percentage of executable response groups which are consistent.

#	Response Options Generated	Groups of Consistent Responses	Groups of Inconsistent Responses	Response Percentage	Consistency Percentage
1	135	112	21	98.52%	84.21%
2	118	104	11	97.46%	90.43%
3	125	103	21	99.20%	83.06%
4	117	99	17	99.15%	85.34%
5	132	97	17	86.36%	85.09%
6	131	116	11	96.95%	91.34%
7	132	107	15	92.42%	87.70%
8	93	80	9	95.70%	89.89%
9	120	98	12	91.67%	89.09%
10	146	127	15	97.26%	89.44%
11	108	92	15	99.07%	85.98%
12	125	105	17	97.60%	86.07%
13	110	95	13	98.18%	87.96%
14	97	81	14	97.94%	85.26%
15	119	102	10	94.12%	91.07%
16	127	104	15	93.70%	87.39%
17	134	112	17	96.27%	86.82%
18	105	92	10	97.14%	90.20%
19	118	99	15	96.61%	86.84%
20	122	99	22	99.18%	81.82%
21	145	122	19	97.24%	86.52%
22	129	109	18	98.45%	85.83%
23	107	96	9	98.13%	91.43%
24	131	103	20	93.89%	83.74%
25	124	95	25	96.77%	79.17%
26	114	94	18	98.25%	83.93%
27	131	103	19	93.13%	84.43%
28	126	111	13	98.41%	89.52%
29	102	82	16	96.08%	83.67%
30	119	95	18	94.96%	84.07%

Table 38. Alternative #2 Arena® Results – Response Consistency

Finally, to determine possible performance differences in the alternative architectures, the results of the two models were compared, specifically the time from response option to executable response. The second column of and the second column were the respective data. First, an F-Test was conducted to determine if the variances of the two data sets were equal. Specifically, the null hypothesis was H_0: $\sigma^2_1 = \sigma^2_2$ and the

test hypothesis was H_1: $\sigma^2_1 \neq \sigma^2_2$. The results are shown in Table 39. Since F > $f_{0.0005}$ (29, 29), the null hypothesis can be rejected and variances are assumed to be unequal.

F-Test: Two-sample for Variances	**Alternative #1**	**Alternative #2**
Mean	16.31342	14.9548
Variance	1.911203	6.914298
Observations	30	30
df	29	29
F	3.617773	
$f_{0.0005}$ (29, 29)	3.566697	
$f_{0.9995}$ (29, 29)	0.280371	

Table 39. F-Test Results

Next, a t-test was conducted to determine if the mean of the two data sets were equal. Since the variances are assumed to be unequal they cannot be pooled. Specifically, the null hypothesis was H_0: $\mu_1 = \mu_2$ and the test hypothesis was H_1: $\mu_1 > \mu_2$. The results are shown in Table 40. Since t > $t_{0.02}$ (43) – One-tail, the null hypothesis can be rejected and it can be assumed that the mean of Alternative #1 is greater than Alternative #2.

t-Test: Two-sample for Mean	**Alternative #1**	**Alternative #2**
Mean	16.31342	14.9548
Variance	1.911203	6.914298
Observations	30	30
Hypothesized difference in means	0	
df	43	
t	2.504906	
$t_{0.02}$ (43) – One-tail	2.41625	

Table 40. t-Test Results

Alternative #2 generates executable responses, on average, in less time than Alternative #1, but with more variance. In addition, Alternative #2 generates consistent executable responses approximately 87% of the time. Since Alternative #1 generates only one executable response for each response option, the consistency of response is 100% by default. The above simulations and analysis demonstrates the possible performance differences between the two alternative designs. However, as discussed in Chapter VII, the reader is warned not to draw specific conclusions on performance of the

alternative system designs from such results. Instead, the reader should be encouraged that modeling and simulation can determine possible performance differences in alternative designs using the architectural framework developed in this thesis.

LIST OF REFERENCES

Ackoff, R.L. (1989) From Data to Wisdom. *Journal of Applied Systems Analysis,* 16, 3-9.

Air Force Doctrine Document 1: Air Force Basic Doctrine (2003) [Electronic Version]. Air Force Doctrine Center.

Alberts, D.S., Garstka, J.J., & F.P. Stein (1999). *Network Centric Warfare: Developing and Leveraging Information Superiority* (2nd Ed.) [Electronic Version]. Washington, D.C.: Department of Defense Command and Control Research Program.

Alberts, D.S. & R.E. Hayes (2006). *Understanding Command and Control* [Electronic Version]. Washington, D.C.: Department of Defense Command and Control Research Program.

Athans, M. (1986). Command and Control (C2) Theory: A Challenge to Control Science [Electronic Version]. *IEEE Transactions on Automatic Control* 32(4), 286-293.

Baran, P. (1964). *On Distributed Communications: I. Introduction to Distributed Communications Networks* [Electronic Version]. Santa Monica, California: The RAND Corporation.

Bindi, V.C., Baker, J., Billington, R., Gallassero, T., Gueary, J., Harts, et al. (1997). *Littoral Undersea Warfare in 2025* [Electronic Version]. Unpublished master's thesis, Naval Postgraduate School, Monterey, California.

Booth, W.C., Colomb, G.G., & J.M. Williams (2008). *The Craft of Research* (3rd ed.). Chicago: The University of Chicago Press.

Boyd, J. (1987). *Organic Design for Command and Control* [Electronic Version]. Unpublished lecture notes. Retrieved February 17, 2009, from: http://www.d-n-i.net/dni/john-r-boyd/.

Boyd, J. (1996). *The Essence of Winning and Losing* [Electronic Version]. Unpublished lecture notes. Retrieved October 23, 2008, from: http://www.chetrichards.com/modern_business_strategy/boyd/essence/eowl_frameset.htm.

Bruegge, B. & A.H. Dutoit (2004). *Object-Oriented Software Engineering: Using UML, Patterns, and Java* (2nd ed.). Upper Saddle River, New Jersey: Prentice Hall.

Buede, D.M. (2000). *The Engineering Design of Systems: Models and Methods* [Electronic Version]. New York: John Wiley & Sons, Inc.

Cebrowski, A.K. & J.J Garstka (1998). Network-Centric Warfare: Its Origin and Future [Electronic Version]. *U.S. Naval Institute. Proceedings* 124(1), 28-35. Retrieved September 8, 2008, from http://proquest.umi.com.libproxy.nps.edu.

Chairman of the Joint Chiefs of Staff Manual 3500.04D: Universal Joint Task List (August 2005) [Electronic Version]. Washington, D.C.: Joint Staff.

Clark, T. & T. Moon (2000, June). Assessing the Military Worth of C4ISR Information [Electronic Version]. In *7th Annual International Command and Control Research and Technology Symposia*, Quebec City, Canada.

Clausewitz, C. von. (1984). *On War* (M. Howard & P. Paret Trans.) Princeton, New Jersey: Princeton University Press.

Committee on C4ISR for Future Naval Strike Groups, Naval Studies Board, Division on Engineering and Physical Sciences (2006). *C4ISR for Future Naval Strike Groups* [Electronic Version]. Washington, D.C.: National Academies Press.

The Cooperative Engagement Capability [Electronic Version] (1995). *Johns Hopkins APL Technical Digest*, 16(4), 377-396. Retrieved July 19, 2008, from http://techdigest.jhuapl.edu/td1604/index.htm.

Defoe, J.C. (1993, January 21). *An Identification of Pragmatic Principles – Final Report* [Electronic Version]. Seattle, Washington: International Council on Systems Engineering. Retrieved September 24, 2008, from http://www.incose.org/ProductsPubs/techresourcecenter.aspx.

Descartes, R. (1850). *Discourse on the Method of Rightly Conducting the Reason and Seeking the Truth in the Sciences* (J. Veitch, Trans.) [Electronic Version]. Edinburgh: Sutherland and Knox. Retrieved September 8, 2008, from http://books.google.com.

Director, Force Transformation, Office of the Secretary of Defense (2005, January 5). *The Implementation of Network-Centric Warfare* [Electronic Version]. Retrieved August 13, 2008, from www.au.af.mil/au/awc/awcgate/transformation/oft_implementation_ncw.pdf.

Field Manual 6-0, Mission Command: Command and Control of Army Forces (2003) [Electronic Version]. Washington, D.C.: Department of the Army.

Forsberg, K., Mooz, H. & H. Cotterman (2005). *Visualizing Project Management: Models and Frameworks for Mastering Complex Systems* (3rd Ed.). Hoboken, New Jersey: John Wiley & Sons, Inc.

George, A.L. (1984). Crisis Management: The Interaction of Political and Military Considerations [Electronic Version]. *Survival* 26(5), 223-234.

Hayes, S., Krulisch, A., & R. White (2008). *Preventing and Winning Wars*. Unpublished manuscript, Chief of Naval Operations Strategic Studies Group XXVII, Newport, Rhode Island.

Hunerwadel, J.P. (2006). New USAF Doctrine Publication: Air Force Doctrine Document 2-1.9, Targeting [Electronic Version]. *Air & Space Power Journal* 20(3). Retrieved February 17, 2009, from http://www.airpower.maxwell.af.mil/airchronicles/apj/apj06/fal06.htm.

Hurley, J.S. (2005, October). Cross-Functional Working Groups: Changing the Way Staffs Are Organized. *Joint Force Quarterly: JFQ,* (39), 91-96. Retrieved December 5, 2008, from Military Module database. (Document ID: 913686111).

Jane's Information Group (2008, March 19). Command and control of US naval forces [Electronic Version]. In *Jane's Fighting Ships*. Retrieved November 26, 2008, from: http://search.janes.com.

Joint Publication 1-02: Department of Defense Dictionary of Military and Associated Terms (2008, May 30) [Electronic Version]. Washington, D.C.: Joint Chiefs of Staff.

Joint Publication 3-60: Joint Targeting (2007) [Electronic Version]. Washington, D.C.: Joint Chiefs of Staff.

Joint Publication 6-0: Joint Communications Systems (2006) [Electronic Version]. Washington, D.C.: Joint Chiefs of Staff.

Kasunic, M. & W. Anderson (2004). *Measuring Systems Interoperability: Challenges and Opportunities* [Electronic Version]. Pittsburgh, Pennsylvania: Carnegie Mellon University.

Keeney, R. L. (1996). *Value-Focused Thinking*. Cambridge, Massachusetts: Harvard University Press.

Klein, G.A. (1988). Naturalistic Models of C3 Decision Making. In S.E. Johnson and A.H. Levis (Eds.), *Science of Command and Control: Coping with Uncertainty* (pp. 4-9). Washington, D.C.: AFCEA International Press.

Lawson, J.S., Jr. (1981). Command and Control as a Process [Electronic Version]. *IEEE Control Systems Magazine* 1(1), 5-11.

Levis, A.H. & M. Athans (1988). The Quest for C3 Theory: Dreams and Realities. In S.E. Johnson and A.H. Levis (Eds.), *Science of Command and Control: Coping with Uncertainty* (pp. 4-9). Washington, D.C.: AFCEA International Press.

Levis, A.H. & L.W. Wagenhals (2000). C4ISR Architectures: I. Developing a Process for C4ISR Architecture Design [Electronic Version]. *Systems Engineering* 11(3), 225-247.

Lynn, J.A. (2004). *Battle: A History of Combat and Culture*. Cambridge, Massachusetts: Westview Press.

Mack, W. P. (1998). *Naval Officer's Guide* (11 Ed.). Annapolis, Maryland: Naval Institute Press.

Marine Corps Doctrinal Publication 6: Command and Control (1996) [Electronic Version]. Washington, D.C.: Department of the Navy.

Mish, F.C., et al. (Ed.) (1994). *Merriam-Webster's Collegiate Dictionary* (10th ed.). Springfield, Massachusetts: Merriam-Webster, Incorporated.

NATO Research and Technology Organization (2002, October). *NATO Code of Best Practice for Command and Control Assessment* [Electronic Version]. Retrieved August 13, 2008, from www.dodccrp.org/files/NATO_COBP.pdf.

NATO Research and Technology Organization (2006, January). *Exploring New Command and Control Concepts and Capabilities – FINAL REPORT* [Electronic Version]. Retrieved August 13, 2008, from http://www.dodccrp.org/html4/research_nato.html.

NATO Standardization Agency (2008). *NATO Glossary of Terms and Definitions (English and French)* [Electronic Version]. Brussels: NATO Headquarters.

Naval Doctrine Publication 6: Command and Control (1995) [Electronic Version]. Washington, D.C.: Department of the Navy.

Payne, C. (2006). *Principles of Naval Weapons Systems*. Annapolis, Maryland: Naval Institute Press.

Perry, W. L., Button, R.W., Bracken, J., Sullivan, T. & J. Mitchell (2002). *Measures of Effectiveness for the Information-Age Navy: The Effects of Network-Centric Operations on Combat Outcomes* [Electronic Version]. Santa Monica, California: The RAND Corporation.

Rice, M.A. & A.J. Sammes (1989). *Communications and Information Systems for Battlefield Command and Control.* London: Brassey's.

Sage, A.P. & J.E. Armstrong, Jr. (2000). *Introduction to Systems Engineering*. New York: John Wiley & Sons, Inc.

Stytz, M.R. & S.B. Banks (2006, June). Metrics for Assessing Command, Control, And Communications Capabilities [Electronic Version]. In *2006 Command and Control Research and Technology Symposia*, San Diego, CA.

Sun Tzu (1971). *The Art of War* (S.B. Griffith, Trans.). London: Oxford University Press.

Sun Tzu (1994). *The Art of War* (R.D. Sawyer, Trans.). Boulder, Colorado: Westview Press.

Sweeney, M.M. (2002). *An Introduction to Command and Control* [Electronic Version]. Unpublished master's thesis, Naval Postgraduate School, Monterey, California.

Van Creveld, M. (1985). *Command in War.* Cambridge, Massachusetts: Harvard University Press.

Washburn., W.R. (2001). Bits, Bangs or Bucks? The Coming Information Crisis [Electronic Version]. *Phalanx* 34(3), pp. 6-7 and 24-27.

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